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Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles

Development of Concepts for an Intelligent Sensing System

David Abbott, Briony Doyle, John Dunlop, Tony Farmer, Mark Hedley, Jan Herrmann, Geoff James, Mark Johnson, Bhautik Joshi, Geoff Poulton, Don Price, Mikhail Prokopenko, Torsten Reda, David Rees, Andrew Scott, Philip Valencia, Damon Ward, and John Winter

Commonwealth Scientific Industrial Research Organisation
Telecommunications and Industrial Physics
Lindfield, New South Wales, Australia

July 2002

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1. Introduction

Project aims

NASA's goal of ageless aerospace vehicles requires the development of vehicles that are capable of structural self-assessment and repair. These functions can be divided between those carried out by distributed sensors and intelligent processing and communication on the skin or within the structure, and those that could be more effectively provided by autonomous robotic NDE agents which could be deployed to monitor damage or integrity of the vehicle structure.

Critical to the success of the Ageless Vehicle program are the development of appropriate technologies for non-destructive evaluation of structures, and the development of strategies and technologies for processing NDE data, storage and communication of NDE information, and analysis of NDE data with capability for intelligent decision-making.

The aim of this project is to develop and critically examine concepts for integrated smart sensing and communication systems that could form the distributed sensing function of a smart vehicle. Such an integrated system may include components deployed for structural monitoring on an NDE agent.

What do we mean by an intelligent sensing system? This will be discussed in some detail later in the report (Section 6), but in general it is one that can reduce the data from a large number of a variety of sensors to concise, useful information; can use this information to form a representation (or perception) of the state of the system being sensed; and, ultimately, can use this representation to develop intelligent strategies and initiate actions to assist the system to achieve its goals. In the present case of an ageless aerospace vehicle, the goals are to avoid damage or to minimize and repair damage, and to do this in a way that is sustainable in the long term.

Purpose and outline of this report

The purpose of this report is to present the results of the project team's considerations of the issues involved in the development of concepts for an integrated vehicle health monitoring system (IVHMS) capable of providing the information necessary for a vehicle to attain agelessness. It is also to propose a hardware and software system that can be developed during the next phases of this project to evaluate and demonstrate some of the concepts discussed. Most of the material presented in this report was produced by a number of Working Groups, which had responsibility for investigating relevant issues in the following areas.

- Sensors, including prioritization of measurands and sensor types.
- Data processing.
- Communications and networks.
- Intelligent systems.
- Computer simulation of complex systems.

- Materials and structures.
- Biological analogues.

Work on materials and structures of next-generation aerospace vehicles was undertaken, even though it is not strictly within the scope of the project, in order to provide a sense of the environment in which a sensor system will be required to operate in the future. This group therefore had a "watching brief" and investigatory and educational functions for the whole team. The group also produced some interesting ideas of its own for materials and structures capable of reconfiguration (morphing) and self-repair.

The only obvious examples of systems capable of intelligent sensing, regeneration and self-repair are biological systems. It is therefore natural that anyone interested in artificial systems with these characteristics should look to biological systems for inspiration and education. Biological systems provide instructive examples of almost all aspects integrated health monitoring, and regeneration and self-repair. In some cases it will be judged that a biological analogue is not appropriate for application in an ageless vehicle (after all, biological bodies are not ageless – they survive statistically rather than individually), or that it is not understood well enough for the analogy to be useful (e.g. thinking and consciousness). However, as has become apparent throughout this work, there are many useful analogies in biology that can be used to guide current thinking and to indicate possible future development directions for materials, structures, repair mechanisms and sensing systems.

It is important to make the point that the considerations of the various Working Groups listed above were not carried out in isolation from each other. There are clearly strong inter-dependencies between these areas, and it is crucial that a holistic approach be taken to the development of an IVHMS. Strong interactions between the groups were maintained by the sharing of personnel, the common availability of documents (via a shared directory), a number of meetings for the whole team (including lectures by local and visiting experts) and some joint meetings of Working Groups.

While it is expected that in the longer term CTIP will contribute significantly to the development of appropriate sensors for ageless systems and of measurement principles and techniques for solving outstanding relevant NDE issues, the main thrust of the present project is to develop concepts for the whole integrated system: for sensing, data processing, storage, communication and decision-making. Therefore, it has been assumed that it is not necessary at this stage to work within a scenario that contains all conceivable threats for all classes of future operational conditions, as long as it contains a sample of possible threats that is representative in terms of the type and severity of potential damage, the time taken for damage to occur or accumulate, opportunities for prior detection and avoidance, the nature and timescale of appropriate responses, and so on. In short, the scenario must be representative in terms of requirements on the functionality of the system, but not necessarily all-inclusive.

The structure of this report is as follows. Some background issues and definitions (for example, of the vehicle types or scenarios that will be considered) will be outlined in the next section. The following two sections contain material generated by the Biological Analogues and Materials and Structures Working Groups. These sections introduce a number of ideas and concepts that will be pursued in later sections of the report. Following this there is a section on sensors, much of which is devoted to the prioritization of measurands and sensor types, but which also discusses some of the sensing issues involved in the development of an IVHMS. This work picks up and continues the work presented in Report 1 (CTIP, 2002) of this project. The next sections discuss intelligence issues (Section 6) and data processing, communications and networks (Section 7), and these are followed by a description of a general-purpose software simulator that is being developed to simulate and act as a test-bed for various aspects of all of these themes. Development and use of the simulator will be a powerful tool not only in testing approaches in each of the separate areas, but also for ensuring that workable holistic concepts result. Finally, a proposal is made for the top-level features of a concept demonstrator based on all of the considerations reported here. Further details will be developed in consultation with NASA staff in time for work to commence early in the 2002/03 financial year. There are a number of Appendices containing relevant documents generated by some of the Working Groups.

Reference

CTIP (2002) *Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles: Threats and Measurands*. CSIRO Telecommunications and Industrial Physics. NASA CR-2002-211772, July 2002.

2. Preliminary Discussions and Definitions

This section contains discussion of some common issues that are pertinent to later sections of the report. It also outlines some common definitions and limitations.

What is meant by an ageless vehicle?

One of the first questions to arise in a program on ageless vehicles is what precisely is meant by agelessness. The literal definition, of course, is that it is capable of remaining in "as new" operating condition indefinitely, regardless of the conditions to which it may be exposed. Yet we would all have considerable doubts that this will ever be possible, and a certainty that it is not desirable: technological development will continue and vehicles and other structures will become obsolete. If ageless technology were available in the 1930s, how many of us today would be happy to do our business travel in a DC3? Perhaps it is more appropriate to aim for an evolving vehicle, or perhaps even a recyclable vehicle.

Ultimately what is required is a vehicle that is capable of completing its mission, with no human intervention for maintenance or repair required. For a space vehicle this may involve a single mission lasting many years or decades. The vehicle may be un-manned or it may contain a self-contained bio-system. Each mission for an aircraft, on the other hand, is relatively short. The aim of agelessness in this case is, first and foremost to ensure that each flight is completed safely, and secondly to remove the need for regular maintenance even though it might be cost effective to carry out some repair functions using human intervention. For an aircraft, reliable vehicle health monitoring would remain a highly desirable objective, even though some aspects of self-repair could be less so.

Requirement for a vehicle health monitoring system

Whether or not self-repairing or regenerating materials and structures can be developed (and it is virtually certain that some degree of self-repair capability will be possible in the near future – see Section 4), and whether or not materials become so advanced that autonomic self-repair or continuous regeneration mechanisms result in genuinely ageless structures without any non-local intervention (which seems a very distant possibility at this time), it will be beneficial to have an integrated vehicle health monitoring system.

In the former case, the detection of threats or resulting damage, as it occurs, using embedded sensors, will reduce vehicle maintenance costs and down-time, and it also removes some present constraints on vehicle design (e.g. related to inspectability and redundancy). This should enable lighter, more efficient vehicles to operate with lower maintenance costs.

In the latter case it will always be desirable for non-local elements of the system to have knowledge of the occurrence of damage, either to appropriately manage the supply of nutrients for repair, and/or to implement mitigation strategies against further damage.

As materials become more advanced the nature of sensors and the way in which they are embedded into the material or structure will almost certainly change, probably moving towards materials with inherent or biomimetic sensing mechanisms. In fact the technologies employed in all elements of the monitoring system will change with time. The only feature that can be confidently predicted is that some form of sensing, communication and supervision or decision-making system will be necessary.

Issues which impinge directly on the identification of threats and sensing requirements for an ageless vehicle are:

- the nature of threats to be considered;
- the nature and purpose of the vehicle;
- the vehicle structure and the capabilities of materials.

The nature of the threats to be considered

A threat is considered to be any event, situation or characteristic that can result in damage to the vehicle or can produce an impairment of its function. Threats will be referred to as external if they result directly from the external environment in which the vehicle is operating (e.g. weather conditions in the atmosphere, cosmic radiation or meteoroids in space), or internal if they are generated internally within the vehicle, or indirectly due to the external environment (e.g. material fatigue, pressure leaks, electronic system failure). Threats, their consequences, quantities that can be measured to detect them (measurands), and possible responses to them will be considered in more detail in Section 5.

It was decided that malicious threats would not be considered explicitly in this work, partly because of the enormous variety of ways in which malicious damage could be inflicted on a vehicle, and by means in the future that we probably cannot imagine now. However, the effects of many forms of malicious damage will be similar to those of accidental or unavoidable damage.

The nature and purpose of the vehicle

There are four significantly different environments, mission requirements, or combinations of these factors, in which future aerospace vehicles are likely to be required to operate. They may be summarized as follows.

A. Space vehicle, which would operate only in space, and never in the Earth's atmosphere. It would dock, and could be serviced if necessary, at a space station. It would not be subject to the rigours of atmospheric travel (turbulence, drag, heat generation, etc.), but flights would be long, leading to a strong requirement for structural reliability and longevity. Such a vehicle may be manned or un-manned. It could carry a shuttle-type vehicle (C) to avoid the need to negotiate an atmosphere at a destination.
B. A space station, in permanent orbit about the Earth (or another planet).
C. A "shuttle"-type vehicle, which commutes between Earth and space (e.g. a space station, the moon, …). It must be capable of handling high-speed atmospheric travel and large accelerations, including the heat of re-entry. Flights will probably

be shorter than for the space vehicle. Human intervention in the maintenance process, if required, could be available on earth or at a space station.

D. An atmospheric vehicle (aircraft). Comparable requirements to present aircraft. Could range from short low-level trips (inter- and/or intra-city) to longer haul (inter-continental) flights. Can probably assume the latter would be fast and high, leading to similar requirements to the shuttle vehicle (C).

This is clearly not an exhaustive list, but it will be used as a representative group of requirements for reference in other sections of this report, in particular the Materials and Structures and the Sensors sections. In general it is only the threats posed by the external environment that are different for the different vehicle types. However, the severity, frequency and relative importance of internal threats may be different, as are the opportunities for and means of repair. These will make important differences in practice.

Vehicle structure and capabilities of materials

This topic is the subject of the section on Materials and Structures (Section 4) and is also discussed in the next section on Biological Analogues. It is difficult to envisage the nature or capabilities of materials in, say, 50 years time. The best that can be done is to look at research trends and new ideas, and to consider the solutions developed by biological evolution. However, the following comments can be made about the requirements of a sensing system, which are (relatively) independent of the capabilities and properties of the materials.

Whether or not the ultimate aerospace vehicle is, in whole or in part, a self-assembling, self-regenerating structure, it is highly likely that it will contain materials that have some capability for self-healing. Such materials are already under development, e.g. composites that contain micro-globules of resin and hardener dispersed within their microstructure, even though in this case the self-repair mechanism is relatively unsophisticated and non-repeatable. We need to consider the implications of self-healing materials for a sensing, communication and supervisory system.

Self-repair of a material or structure requires that, at some level, the material or structure must "know" it has been damaged. The following are possible scenarios for damage detection and repair.

1. The damage could be repaired as part of a continuous regeneration process. This might be appropriate for slowly accumulating damage, such as may occur due to fatigue, wear, corrosion or radiation. In this case the regeneration cannot be simple replacement: it must be based on information about the undamaged material.
2. The damage is detected and repaired "autonomically" by the material or its local environment (i.e. without reference to other parts of the structure), not by a continuous process but "on demand" in response to the detection of damage. If this is to be carried out repeatedly, as required, then both information (possibly stored locally) and a supply of replacement material on demand are required.
3. The damage is detected, locally or remotely, and the repair process is initiated (and possibly controlled) by another part of the structure.

These three scenarios require rather different balances to be struck between sensed information that is used locally to initiate and control repair/healing/regeneration, and that which is communicated to other regions of the structure.

While scenario 1 may not actually require the active detection of the particular forms of slowly accumulating damage, such "autonomic" repair would imply that the system continuously regenerates at a rate that does not depend on the rate of damage accumulation, yet it regenerates sufficiently quickly that damage is repaired before it can accumulate beyond some critical level. The efficiency of such continuous regeneration would need to be examined: while materials may be recyclable, the process would consume energy. In any case, it is likely that a supervisory system would want to know if this sort of damage was occurring, and its rate of progression.

Scenario 2, which allows for local repair/regeneration, but "on demand" in response to the detection of damage, requires some form of communication to another part of the structure, at least for the supply of replacement material. Scenario 3 requires communication of damage information to the part of the structure responsible for repair, in all cases. Therefore, as stated above, it seems likely that whatever the capabilities of the materials for self-repair or regeneration, there will be a requirement for knowledge of the occurrence and nature of damage to be communicated to some region of the structure remote from the damage site.

Another significant issue relating to material capabilities is that of information. Any self-repairing or regenerating material requires information, energy and a source of new material (nourishment).

- For biological systems, the information is stored locally in the cell nuclei. Thus each cell of the system contains a huge amount of information, much of which may not be relevant at that specific location. The provision of nourishment for regeneration, and the removal of waste products, are carried out differently according to the type and complexity of the system. The central supervisory system (central nervous system, brain) in higher animals may play a role in damage repair (and certainly in implementing strategies for damage minimization), but in simpler systems the information required for repair and regeneration appears to be maintained entirely locally.
- For the current generation of self-healing composites, the "information" content and the ability to repair the material are both very limited. Only one phase of the composite (the epoxy matrix) can be repaired, and the required information is, presumably, contained in the distribution and content of the adhesive globules, and thus is entirely local.
- In general, one would imagine that the information required to repair a material or structure would be most efficiently maintained in some combination of local and distributed (or centralized) storage.

As a final (self-evident) comment, it is worth noting that biological models of self-repair are somewhat imperfect:

- There is a very obvious process of ageing, ultimately due to a loss or corruption of local information for regeneration.
- Even in the absence of ageing, over-use injuries (in some cases analogous to fatigue in engineering materials), stress fractures, wear (e.g. at joints), etc. occur that are not adequately repaired without external intervention.
- Biological systems are successful statistically rather than individually. The aim here is to design vehicles with as close to 100% survivability as possible.

Thus, biological models can provide very useful and interesting ideas for ageless vehicles, but their limitations must be recognized.

Reference models

In a number of sections of the report reference will be made to models for a simplified vehicle and/or environment. This is done in order to focus the discussions and to provide specific examples. Both the Materials and Structures (Section 4) and Sensors (Section 5) sections will make reference to the requirements for the four vehicle types A-D outlined above.

Other sections make reference to a more generic structure, which is also used as the conceptual basis for the simulation software. This consists of a skin that is modular in structure: the modules could be thought of as "tiles" or "scales". These modules could be of any shape, but triangular tiles have been adopted in most cases. Each tile contains one or more sensors, a processor unit and memory, communications capability and an energy store. The model is assumed to exist in an environment where there is only a small number of threats, all of which (or their consequences) can be detected by the sensors on the tiles.

Reference

CTIP (2002) *Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles: Threats and Measurands*. CSIRO Telecommunications and Industrial Physics. NASA CR-2002-211772, July 2002.

3. Analogues in Biological Systems

3.1 Introduction

Biological systems are the only obvious examples we have of many of the attributes required of ageless structures. It is therefore inevitable that we look to biology to provide ideas and guidance in areas such as intelligent sensing, self-repair and regeneration, integrated sensing systems, structural adaptivity, intelligence, etc. References to biological analogues have already been made in the first two sections of this report, and further references will be made in almost all succeeding sections. This section outlines some of the biological mechanisms that are, or may be, relevant. There was no attempt to study all biological systems or mechanisms of interest. The aim was to obtain accurate information about a necessarily limited number of systems from standard sources or from people with expertise in the relevant area. It is important to note that biological analogues are not expected to be directly applicable to systems or functions that need to be developed for ageless vehicles or integrated health monitoring systems. They are studied to provide ideas and inspiration.

Adaptable, self-repairing structures are a natural occurrence in biological systems. The mechanisms by which living creatures repair themselves and adapt to their environment may be applicable to the development of a self-repairing and adaptable aerospace vehicle. All living creatures have methods for survival, but it is not possible to compare every system for possible analogues to the development of an ageless vehicles. The topics covered in this report are based on models that were highlighted during group discussions as having relevance and that the authors thought were particularly relevant, and which lay within their expertise.

The particular topics chosen, and covered here only in broad outline, are the mammalian nervous system and its response to injury, wound healing in humans, regenerative capability in the animal kingdom, and herd behaviour in animals. The purpose of these overviews is not to provide a detailed exposition of the subjects themselves, but simply to point out principles that may eventually be applicable to ageless vehicles and/or to integrated vehicle health monitoring systems. Some very speculative ideas are introduced.

3.2 Mammalian nervous system – normal function

This subsection contains a very brief, simplified and superficial overview of the normal function of the mammalian nervous system, and the following subsection outlines its response to injury. These are both enormous subjects of great potential relevance to sensing, decision-making and repair systems in ageless structures. There are many sources of further information about these topics, including the text by Sherwood (2001). It is a pleasure to thank Professors Phil Waite and Mark Rowe, of the Faculty of

Medicine, University of NSW, for their generous assistance with our understanding of these topics.

Neurons

The neuron is a cell that is the basic communication unit of the nervous system. It has a cell body, which contains the nucleus. Dendrites and axons connect it to other neurons or to cells that are activated by the nervous system (such as muscles). Axons may vary in length from 1 mm to more than 1 metre. Communication along the axon is achieved by ionic conduction, of which there are various complex mechanisms.

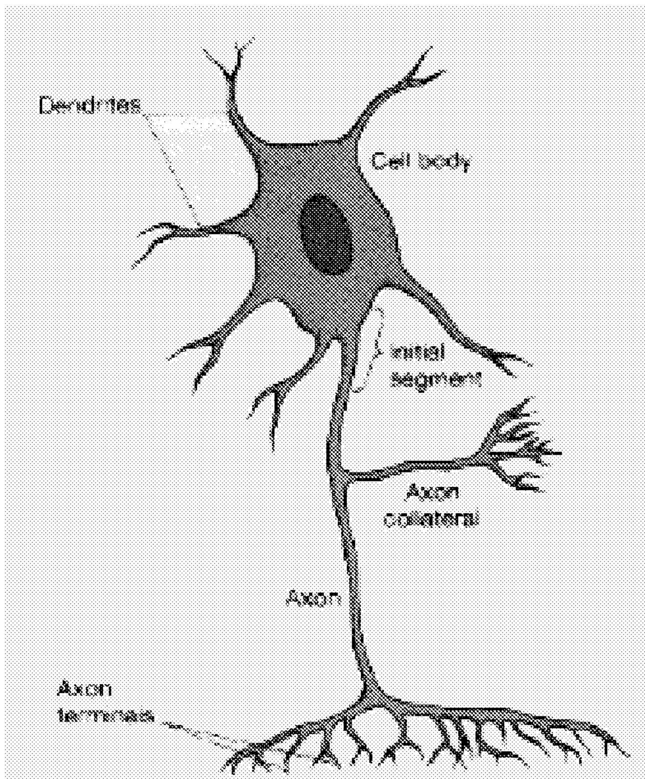

Figure 3.1: Components of a neuron (http://www.bme.jhu.edu/~jsorger/LSD/neuron.html , Vander et al., 1994). A bundle of neurons is called a nerve. Nerves can consist of a few to hundreds of neurons, all travelling in parallel.

Central nervous system

The central nervous system is the control centre for the body, consisting of the brain and spinal cord. It is composed of neurons and glial cells, which help with structure and function. The central nervous system is supported within the cerebrospinal fluid (CSF), a carefully chemically balanced liquid that cushions the brain against shock. It also has a function in the exchange of materials between the blood and the brain. The central nervous system is well protected by bony structures (the skull and spine) and the CSF.

Glial cells are divided into three types: astrocytes, which provide structural support and help clean up any ionic imbalance in the CSF; microglia, which play an immune role as phagocytes (attacking bacteria and other foreign materials); and oligodendrocytes, which form a myelin sheath around the nerve cells to facilitate faster communications.

The careful balance of chemicals in the CSF is maintained by the blood brain barrier, which limits passage of substances from the blood to the brain. Only substances that are specifically required can cross the barrier, and they are carried across as required by a process called active transport.

The full complement of neurons is achieved very early on in growth, usually prior to birth, with no subsequent replacement. However, the nervous system is not completely hard wired – neural networks and the connections between neurons can change all through adulthood. All memory, for example, is created by modification of neural circuitry. Reinforcement of a memory helps with the rewiring, although exactly how this is done is not really understood.

Peripheral nervous system

The peripheral nervous system extends from the central nervous system to all extremities of the body. It contains the nerves that transmit sensed signals from muscles, skin and other organs to the central nervous system, and transmit driving (motor) signals in the opposite direction. It consists of the axons of neurons and Schwann cells; the nuclei of the neurons remain protected inside the central nervous system. The Schwann cells provide myelination (to provide faster signal conduction) and structural support for the axon, and also play a role in repair, of which more in later sections.

Reflexes

Reflexes are the result of hardwiring between sensory and motor nerves, which causes an automatic response before the brain is aware of the stimulus. The main role of these reflexes is to react automatically to pain in order to avoid injury (such as automatically taking your hand away from a hot object). However, other reflexes help with maintaining balance, by automatically adjusting muscles to cope with additional strain.

A reflex begins with a sensation, a signal from a sensor, which travels the normal path back to the brain. The sensory nerve is also attached to a motor nerve in the spinal cord, and so activates a motor response as well as providing information. A reflex can be overridden by actively (consciously) contracting the muscles that oppose the reflexive motion, as well as inhibiting the reflex response.

Olfactory mucosa cells

Neurons in the olfactory mucosa, connecting the sinuses to the brain, are the only neurons that are born after birth and that continue to divide throughout adult life. Olfactory ensheathing cells are specialized glial cells of the olfactory mucosa that maintain axonal growth from the mucosa to the olfactory bulbs (guide the regrowing nerve cells on their path through the central nervous system). Like Schwann cells, olfactory ensheathing cells continue to divide throughout life, but unlike Schwann cells, which are confined to the peripheral nervous system, olfactory ensheathing cells can enter the central nervous system by guiding olfactory axons to their target destinations in the olfactory glomeruli. They are the only glial cells known to be able to travel across the boundary between the peripheral and the central nervous systems. This function means that these cells may have a function in the healing of the central nervous system (Lu and Waite, 1999). Ramón-Cueto and colleagues recently demonstrated that implantation of olfactory ensheathing cells after complete spinal cord transection could restore both structure and function to the injured animal (see Erigel, 2000).

Possible relevance to an ageless vehicle

The mammalian nervous system is a possible model for the communication and decision-making systems of an ageless vehicle. The concept of defined pathways and varying speeds of communication may be relevant to the concept demonstrator, facilitating the detection and evaluation of damage. The human brain is the best biological model for high-level cognitive processes, though recent work in artificial intelligence has moved away from its traditional goal of understanding and replicating human intelligence. The chemical processes involved are highly complicated, and would probably need to be simplified in any prototype. The high number of components in such a system makes it difficult to model. There are also problems with injury, as outlined in the next section.

Therefore, while it is unlikely that the mammalian nervous system would be used as an explicit model for the sensory system in an ageless vehicle, it provides many useful ideas as well as some features, such as lack of robustness, which should be avoided.

3.3 Mammalian nervous system – response to injury

Central nervous system

The capacity for healing in the central nervous system is severely limited. With the exception of olfactory neurons, as mentioned in the previous section, neurons do not reproduce after birth. Hence, damage to the central nervous system usually results in irreparable damage, as the neurons that die will not be replaced.

In addition, the shielding that protects the brain and spinal cord from damage may actually contribute to exacerbation of damage once it has occurred. The inflammation induced by injury is contained within the protective structure and so increases the pressure on the brain, leading to secondary damage. There are three ways that secondary damage can occur.

1. The body increases blood supply to the damaged area (for the purpose of combating infection and providing supplies for healing). This causes swelling, increasing the pressure in the area, leading to a loss of blood and oxygen supply, resulting in increased swelling as the body tries to compensate, and so on. This cascade can cause much more damage and cell death.
2. The damage often causes the breakdown of the blood-brain barrier, which allows unwanted cells and chemicals to enter the brain, causing increased damage.

3. As neurons die, their store of chemicals leaks, which causes over-excitation of surrounding cells, causing those cells to die, and so on, in another dangerous cascade.

The most effective method the body has for reducing the cascading death in 1 and 3 is by apoptosis. Apoptosis is an important process that results in intentional programmed cell death: every cell has an inbuilt mechanism that, if triggered, causes the cell to destroy itself by activating intracellular protein-snipping enzymes that cut the cell into small disposable pieces. The breakdown products are packaged in a way that prevents damage to surrounding cells, and can be recycled for other purposes. Apoptosis occurs in a range of circumstances, including normal tissue turnover in the body as well as in the removal of aged, damaged or mutated cells.

Glial cells work to reduce damage after injury to the central nervous system. Part of their function seems to actually be reducing the regrowth of damaged nervous cells. As a price of the complex structure of the brain, regrowth cannot be allowed at the risk of interference with proper function. Astrocytes form very dense scar tissue that axons cannot grow through. It is thought that oligodendrocytes also actively prevent growth of neurons.

The only exception to the glial cells preventing growth of nervous tissue is in olfactory tissue, where olfactory ensheathing cells guide the regrowing olfactory neurons from the peripheral nervous system into the central nervous system.

Peripheral nervous system

Peripheral nerves have greater capacity to regenerate, but only if the cell body, containing the nucleus of the cell, is undamaged. This is usually the case as only the axons of the cells are in the periphery.

Schwann cells are very effective in supporting the regrowth of neurons in the periphery. They assist the macrophages in clearing away the dead end of the axon, and then multiply to form a guiding sheath for the axon to grow back down. Meanwhile, the neuron grows tendrils to try to find the path for regrowth. Once it finds the path, it concentrates its growth along it. For this reason, the regenerative capacity of the neuron is greatest after a crush type injury, as the break between the living neuron and its original path is minimal. In an injury where the neuron is severed, this is not the case, and there is the additional risk of collagen scar tissue forming and blocking the route for regrowth. It is not always the case that the axons reach their original point of activation, particularly after a severing injury, but the brain is able to retrain to cope with this.

If the sprouts the neuron grows in the attempt to find its original path do not succeed, they may tangle with the tendrils from other neurons nearby, and form a neuroma. This network of raw nerve endings is usually very painful. It is part of the cause of phantom limb pain, as after amputation the neurons still try to find a path that doesn't exist. The other cause of phantom limb pain after amputation is that the area of the cortex originally dedicated to the now amputated part is rewired for nearby parts.

Possible applications to ageless vehicles

This may be an effective model for the way an ageless vehicle copes with damage to its communication pathways. A high level processing capability would probably be required, so a model of the way in which creatures with high-level cognition cope with injury is worth considering.

As an individual concept, apoptosis could be highly applicable to any ageless structure that is composed of separately functioning units (e.g. "tiles"). A tile that is capable of realising it is beyond repair, and taking action to reduce the confusion created by its generating false signals, as well as possibly signalling that it must be replaced, would be very useful.

The central nervous system cannot heal injury to itself. It is not clear why this is so: perhaps the risks of imperfect repair in such a complex structure are too great, perhaps the dangers of implementing repair processes into the delicate chemical and cellular mix are too great (as will be seen in the next subsection, repair processes in blood vessels and soft tissue require a complex array of specialized molecules), or perhaps it is a result of Darwinian pressure for the species rather than the individual to survive. The evolution of a complex nervous system and intelligent behaviour greatly enhanced survival prospects, clearly to a greater extent than it was hindered by the lack of a repair mechanism.

The central nervous system in mammals is vulnerable to damage by virtue of its centralization. Information processing is concentrated in the brain, and all communication paths are connected directly to the central nervous system; there are no redundant paths. The only defence the system has against damage is its rigid protective enclosure, and it has no capacity for self-repair. These are important characteristics of the mammalian nervous system that would need careful consideration prior to adoption for a vehicle that is required to be 100% survivable. However, there are established methods of assisting the healing process for the central nervous system, and it may be possible to develop comparable methods for an ageless vehicle.

3.4 Wound healing in humans

The interest in this topic is that it provides examples of mechanisms of self-repair of material that have evolved over millions of years. The mechanisms are extremely complex, but the principle of relevance is that of multi-stage repair processes, with multiple pathways, or multiple process redundancy. Blood clotting is considered first, then the overall process of tissue healing, and finally some comments are made about the equalization of blood flow. Further information about these topics can be found in general physiology texts such as Sherwood (2001) and Ganong (1993).

The clotting of blood

Damage to the circulatory system needs to be rapidly repaired to prevent excessive blood loss. This is done, for small blood vessels, by an automatic chemical reaction that clots the blood at the point of damage and stimulates the circulatory system to reduce the blood flow to the damaged area. Platelets in the blood automatically attach themselves to exposed collagen in the damaged wall of the blood vessel, forming a temporary, loose seal over the injury. The whole process is known as haemostasis, and it involves the following three major steps.

1. Vascular spasm, an inherent response that constricts the vessel, reducing blood flow and, consequently, blood loss.
2. Formation of a plug by blood platelets (thrombocytes), that aggregate at a vessel defect as a result of multiple feedback mechanisms triggered by platelets that stick to exposed collagen at the site of the injury: the aggregating platelets release chemicals, adenosine diphosphate (ADP) and thromboxane (A_2) that encourage further platelet aggregation.
3. Blood coagulation (clotting), which transforms the blood from a liquid to a solid gel, strengthening and supporting the platelet plug and reinforcing the seal over the broken vessel.

Figure 3.2 shows the complex process of blood clotting in humans, a multi-stage, multi-pathway process; the figure is shown simply to illustrate the complexity of the process. The various factors that appear in the diagram are molecules that are present in blood plasma. They are (mostly) designated by Roman numerals in the order in which they were discovered. They are normally (i.e. in the absence of injury) inactive.

There are two separate pathways distinguished in the figure. The intrinsic pathway is activated by exposure of the plasma enzyme prekallikrein to collagen at a damaged vessel surface. It is converted to kallikrein and starts a chemical chain reaction of activation of the various clotting factors, ultimately resulting in the formation of fibrin, an insoluble thread-like molecule.

The extrinsic pathway causes clotting of blood that escapes from blood vessels into the surrounding tissue during injury. The latter stages of the two pathways, from the activation of factor X, are identical, the ultimate step being the production of fibrin from the blood plasma protein fibrinogen. Fibrin molecules form a loose net-like mesh that traps the cellular elements of the blood, forming a clot.

Although this multi-step clotting process may seem inefficient and possibly prone to error, the advantage is the amplification that occurs at many of the steps. One molecule of an activated factor can activate perhaps a hundred molecules of the next factor in the sequence. In this way, the clotting process can be rapidly activated as a result of the initial activation of only a few molecules at the first step of the sequence. It is interesting to contemplate the possibility of such an accelerating process for the temporary sealing of a hole in a pressure vessel.

How does the process stop, to prevent widespread clotting from plugging up blood vessels throughout the body? After participating in the local clotting process, the large numbers of activated factors are rapidly de-activated by enzymes and other factors present in the blood plasma.

It is worth noting that the processes of haemostasis are only really effective for repairing injury to the smaller blood vessels. Bleeding from medium and large vessels usually cannot be stopped by these mechanisms alone, and other measures, often involving conscious intervention, may be required (i.e. first aid). Examples range from elevation of the bleeding part to reduce blood flow pressure, to surgical repair of the vessel.

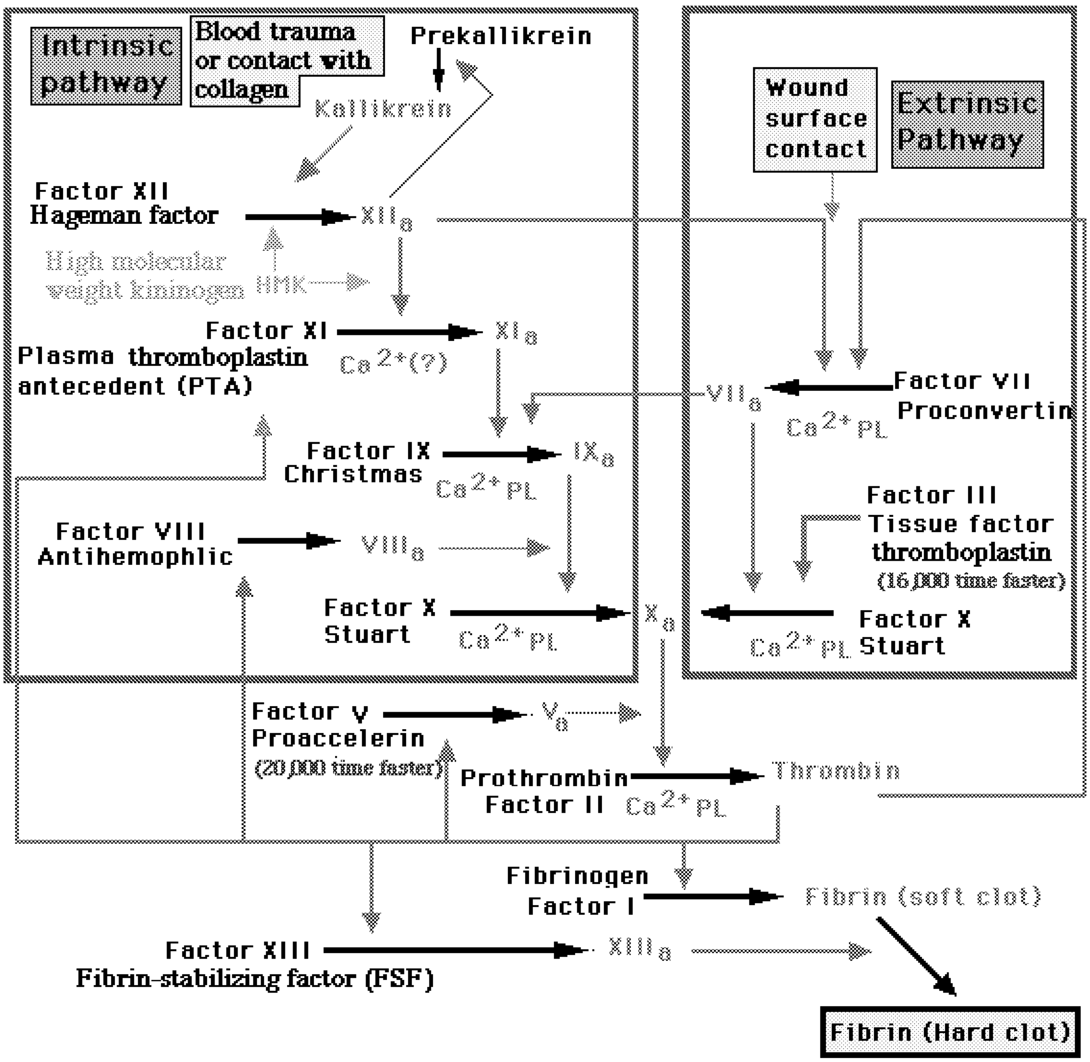

Figure 3.2: Blood clotting pathways in humans (Perez, 2001). (http://ntri.tamuk.edu/homepage-ntri/lectures/clotting.html)

Tissue healing

The repair of damaged tissue is also a multi-stage process, which, for soft tissue, usually includes the repair of blood vessels and blood clotting.

Tissue healing requires two distinguishable functions. Firstly there is a requirement for the body to respond to the introduction of foreign material (e.g. bacteria) into the wound. This is carried out by the immune system. Secondly there is the obvious need to repair the tissue.

One of a number of non-specific immune responses that occur as a result of tissue injury, and one that is significant to the healing process, is inflammation. The ultimate function of inflammation is to bring to the invaded or injured area plasma proteins and phagocytes, which destroy and inactivate the offending agents, remove debris, and prepare for subsequent healing and repair. Inflammation is itself an extremely complex and interesting multi-phase process, but it is probably not of particular relevance to possible repair mechanisms in engineering materials. It might become relevant if engineered structures were to be grown biologically, or in the recycling of materials. This is not to say that something akin to an immune response might not be required if a space vehicle was punctured by a meteoroid; there are certainly biological materials, and possibly living microbes, on meteoroids or astronomical bodies within the solar system and possibly external to it (e.g. Davies, 1998).

The inflammatory process is usually accompanied by swelling, and this can present dangers in some cases, such as in the healing of tissue in enclosed volumes. This can occur in brain injury, and is referred to in subsection 3.3 above.

Healing of the tissue proceeds when the inflammatory process has cleared the area for repair. In some tissues (e.g. skin, bone, liver), healthy organ-specific cells surrounding the injured area undergo cell division to replace lost cells, often resulting in perfect repair. However, in non-regenerative tissues such as nerve and muscle, lost cells are replaced by scar tissue. Large quantities of the protein collagen are secreted in the vicinity of the injury, and this results in the formation of the scar tissue. Even in tissue as readily replaceable as the skin, scar formation often takes place when deep wounds permanently destroy complex underlying structures such as hair follicles or sweat glands.

There is an interesting lecture on wound healing at:
http://www.medinfo.ufl.edu/cme/grounds/mast/index.html (Mast, 1999).
One strong idea comes out of this lecture – multiple redundancies in mechanisms of wound healing. For most processes in wound healing, there are a number of ways each process can be activated, which gives some allowance for problems in any of the systems. Further information is given at: http://www.wound-healing.net/ (ALtruis, 2002).

Tissue healing is a much slower process than the rapid response of, for example, blood clotting. The nature of different responses to damage, and the different time scales on which they occur, are discussed in Section 5.

Equalization of blood flow

Before reading this section, it is necessary to have a basic idea of the cardiovascular flow path in the body. Taking the heart as the starting point, the blood flows out into the arteries, then to the arterioles and finally to the capillaries, which is the point of greatest contact with the body. It then returns to the heart via the veins.

The body adjusts flow paths around the body for a number of reasons, one of which is to help cope with injury. When an injury occurs, the body reacts by increasing the heart rate to counter the loss of blood and allow relatively uninterrupted flow to vital organs. At the same time, blood to the actual injury site is initially reduced by contraction of the arterioles. Once blood loss is partially controlled, with a soft platelet clot, the supply of blood to the injured site is increased above normal levels to facilitate the healing process (See ALtruis (2002), http://www.wound-healing.net/).

The body uses several basic principles to control the flow of blood around the body: globally by changing the heart rate and/or locally by constricting or dilating blood vessels.

- Heart Rate: by moderating heart rate, the cardiovascular throughput is increased.
  Cardiac Output = heart rate × stroke volume.
  The body is capable of altering both parameters to change the cardiac output, and hence the rate of flow of blood around the body.
- Arterioles: the arterioles are the main components of the cardiovascular system that are able to constrict and vary their radius, r. They thereby adjust the overall resistance of the blood flow circuit, and so adjust overall flow:

$$R \propto \frac{1}{r^4}, \text{ Flow Rate } = \frac{\Delta P}{R} \Rightarrow \text{Flow Rate} \propto r^4$$

where ΔP is the pressure gradient and R is the resistance of the blood vessels.

The function of the heart and arterioles are largely automatically regulated by feedback, or by hormonal response (Sherwood, 2001).

Comparable strategies may be required in self-repairing structures if nutrients or materials for repair are circulated as fluids. They may also be adopted in other self-repairing fluid circulation systems to reduce losses (e.g. water, liquid fuels, gases, …).

Possible relevance to ageless vehicles

In response to injury, the human body responds with complex, multi-stage processes, beginning with blood clotting, followed by slower tissue healing. The equalization of blood flow optimizes these processes. Such staged repair processes, possibly with multiple pathways or multiple process redundancy, are likely to be necessary in the repair of sudden, serious damage to an ageless vehicle. For example, the response to a rupture caused by an impact, may be to first seal off the affected section of the craft to prevent further exposure of the interior of the craft (perhaps with associated loss of pressure), then to establish a temporary seal over the breach (to allow repressurization, or to restore an aerodynamic surface and to facilitate complete repair), and finally to restore a fully functional, as-new surface, which may include surface-mounted sensors and communications hardware. As in wound healing, each of these stages would take longer than the previous one.

3.5 Regenerative capability in the animal kingdom

Virtually no group of organisms lacks the ability to regenerate something. This process, however, is developed to a remarkable degree in lower organisms, such as protists and plants, and even in many invertebrate animals such as earthworms and starfishes. Regeneration is much more restricted in higher organisms such as mammals, in which it is probably incompatible with the evolution of other body features of greater survival value to these complex animals.

<u>*General mechanism of regeneration*</u>

1. Conditions for regeneration

Regeneration only occurs in the presence of the following three factors. Firstly, there must be a wound, although the original appendage need not necessarily have been lost. Secondly, there must be a source of blastema cells, a mass of undifferentiated cells that has the capability to develop into an organ or appendage, derived from remnants of the original structure or an associated one. Thirdly, there must be an external stimulation, which often involves the nervous system. An adequate nerve supply is required for the regeneration of fish fins, taste barbels, and amphibian limbs. In the case of many tail regenerations, the spinal cord provides the necessary stimulus. Lens regeneration in salamander eyes depends upon the presence of a retina. The physiological stimulus for regeneration is always associated with the function of the structure to be regenerated. It therefore appears that regeneration is driven by the recovery of deficient functions rather than simply by the replacement of lost structures.

The requirement to recover lost functionality is of further importance in suppressing excess regeneration. If regeneration did not depend upon a physiological stimulus there would be nothing to prevent simple wounds growing whole new appendages.

What is not well known is why regeneration fails to occur in many cases such as in the legs of frogs or the limbs and tails of mammals. The nerve supply, and consequently the stimulation it provides, might be inadequate, for regeneration is sometimes induced by an artificial increase in the number of nerves. This cannot be the whole answer, however, because not all appendages depend on nerves for their regeneration: newt jaws, salamander gills, and deer antlers do not require nerves to regenerate. It is possible that the failure to regenerate relates to the ways in which wounds heal. In higher vertebrates there is a tendency to form thick scar tissue in healing wounds, and this may act as a barrier between the epidermis and the underlying tissues of the stump. In the absence of direct contact between these two tissues, the stump may not be able to provide the blastema cells required for regeneration.

2. The regeneration process

Following amputation, an appendage capable of regeneration develops a blastema from tissues in the stump just behind the level of amputation. These tissues undergo drastic changes. Their cells, once specialized as muscle, bone, or cartilage, lose the characteristics by which they are normally identified (dedifferentiation); they then begin to migrate toward, and accumulate beneath, the wound epidermis, forming a rounded bud (blastema) that bulges out from the stump. Cells nearest the tip of the bud continue to multiply, while those situated closest to the old tissues of the stump differentiate into muscle or cartilage, depending upon their location. Development continues until the final structures at the tip of the regenerated appendage are differentiated, and all the proliferating cells are used up in the process.

The blastema cells seem to differentiate into the same kind of cells they were before, or into closely related types. Cells may perhaps change their roles under certain conditions, but apparently rarely do so. If a limb blastema is transplanted to the back of the same animal, it may continue its development into a limb. Similarly, a tail blastema transplanted elsewhere on the body will become a tail. Thus, the cells of a blastema seem to bear the indelible stamp of the appendage from which they were produced and into which they are destined to develop. If a tail blastema is transplanted to the stump of a limb, however, the structure that regenerates will be a composite of the two appendages.

3. Polarity of regeneration

Each living thing exhibits polarity, one example of which is the differentiation of an organism into a head, or forward part, and a tail, or hind part. Regenerating parts are no exception; they exhibit polarity by always growing in a distal direction (away from the main part of the body). Among the lower invertebrates, however, the distinction between proximal (near, or toward the body) and distal is not always clear-cut.

When planarian flatworms are cut in half, each piece grows back the end that is missing. Cells in essentially identical regions of the body where the cut was made form blastemas, which, in one case gives rise to a head and in the other becomes a tail. What each blastema regenerates depends entirely on whether it is on a front piece or a hind piece of flatworm; the real difference between the two pieces may be established by metabolic differentials. If a transverse piece of a flatworm is cut very thin – too narrow for an effective metabolic gradient to be set up – it may regenerate two heads, one at either end. If the metabolic activity at the anterior end of a flatworm is artificially reduced by exposure to certain drugs, then the former posterior end of the worm may develop a head.

Appendage regeneration poses a different problem from that of whole organisms. The fin of a fish and the limb of a salamander have proximal and distal ends. By various manipulations, however, it is possible to make them regenerate in a proximal direction. If a square hole is cut in the fin of a fish, regeneration takes place as expected from the inner margin, but may also occur from the distal edge. In the latter case, the regenerating fin is actually a distal structure except that it happens to be growing in a proximal direction.

Amphibian limbs react in a similar manner. It is possible to graft the hand of a newt to the nearby body wall, and once a sufficient blood flow has been established, to sever the arm between the shoulder and elbow. This creates two stumps, a short one consisting of part of the upper arm, and a longer one made up of the rest of the arm protruding in the wrong direction from the side of the animal. Both stumps regenerate the same thing, namely, everything normally lying distal to the level of amputation, regardless of which way the stump was facing. The reversed arm therefore regenerates a mirror image of itself.

Clearly, when a structure regenerates it can only produce parts that normally lie distal to the level of amputation. The participating cells contain information needed to develop everything "downstream," but can never become more proximal structures. Regeneration, like embryonic development, occurs in a definite sequence.

These examples of regeneration, both natural and artificially distorted, lead to the possibility of growth of artificial biological structures. This topic is briefly visited in the next section (Section 4) of Materials and Structures.

Invertebrates / Coelenterates

(Phylum Coelenterata – Hydra, jelly fish, sea anemones, corals.)
The vast majority of research on coelenterates has been focused on hydras and some of the colonial hydroids. If a hydra is cut in half, the head end reconstitutes a new foot, while the basal portion regenerates a new hydranth with mouth and tentacles. This seemingly straightforward process is deceptively simple. From tiny fragments of the organism whole animals can be reconstituted. Even if a hydra is minced and the pieces scrambled, the fragments grow together and reorganize themselves into a complete whole. The indestructibility of the hydra may well be attributed to the fact that even the intact animal is constantly regenerating itself. Just below the mouth is a growth zone from which cells migrate into the tentacles and to the foot where they eventually die. Hence, the hydra is in a ceaseless state of turnover, with the loss of cells at the foot and at the tips of the tentacles being balanced by the production of new ones in the growth zone. Figure 3.3 is a diagram showing the lifecycle of common coelenterates.

Flatworms and Annelids are other examples. These animals seem to be the only ageless systems on Earth. The concept is very interesting. Further references: Gaidos et al. (1996), Encyclopaedia.com (2002).

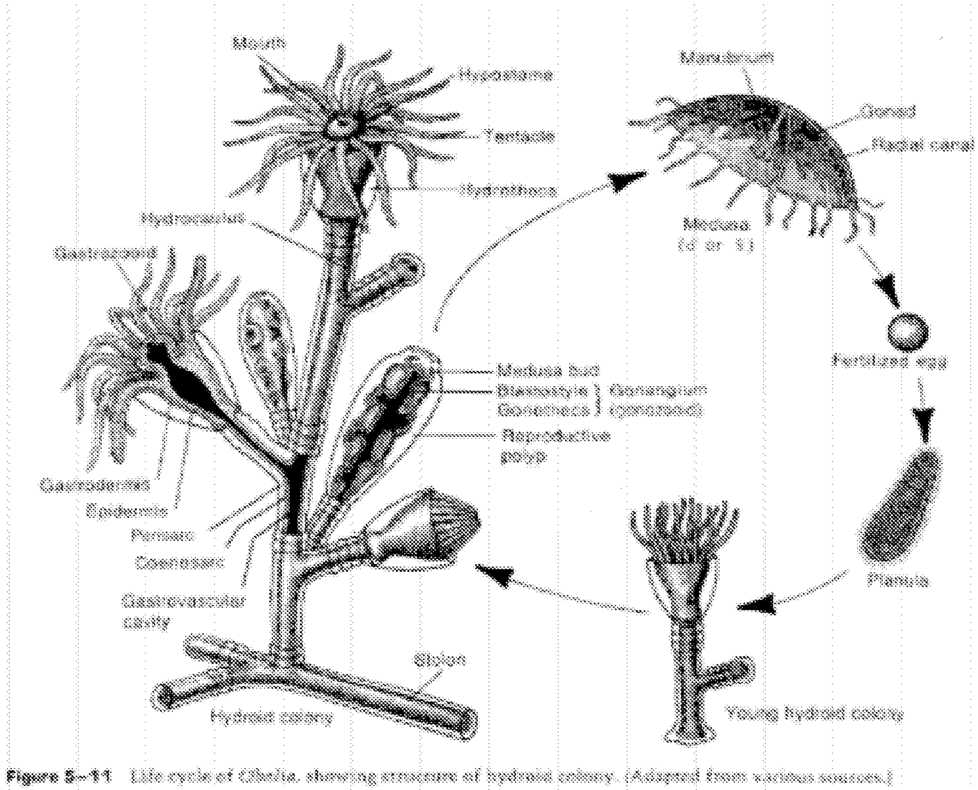

Figure 3.3 The life cycle of *Obelia*, from
http://www-personal.umich.edu/~vmckenna/coral4.html

Lizards losing and regenerating their tails

Lizards also regenerate their tails, especially in those species that have evolved a mechanism for breaking off the original tail when an enemy grasps it. When the lizard tail regenerates, however, it does not replace the segmented vertebrae. Instead, there develops a long tapering cartilaginous tube within which the spinal cord is located and outside of which are segmented muscles. The spinal cord of the lizard tail is necessary for regeneration, but the regenerated tail does not reproduce the ganglia that are normally associated with it. Occasionally, a side tail may be produced if the original tail is broken but not lost.

Speculative possibilities based on principles of biological regeneration

It is tempting to speculate that structures of an ageless vehicle could eventually follow a similar construction principle to that of the coelenterates: a multi-chamber, multi-layered skin structure, made out of constantly regenerating subunits. The subunits, which could be formed like tiles or scales, combine structural, connecting, sensing, transmitting and other properties. However, this is clearly not a short-term prospect.

For adaptive shape control, the principle of regeneration could be combined with that of bone growth and restructuring: the system would be able to maximize structural needs at the places where they are most required, providing strength reinforcement, laminar streaming, structural optimization and so on. The subunits, or "tiles", would be built with integrated sensors and information processing systems.

The metabolism (recycling) process in nature shows that nearly every biological structure (or at least those that live on the surface of the Earth) can be made out of carbon, oxygen, hydrogen, nitrogen, sulphur and a few other elements, by using light (sun) energy. Clearly, though, not all modern materials can be produced this way. However, if future developments combine it with the silicon chemistry, we would be able to make glass and carbon fibres, glues, tubes, and so on, and after usage decompose and resynthesize it.

Tail regeneration in lizards may be a model for methods for an ageless vehicle to cope with major damage. There are many lessons to be learnt: the immediate seal off process, ensuring no one part of the vehicle is essential to survival, and patterns for regrowth. This particular model only applies to non-essential components, since the regrowth is very slow, and the lizard works without its tail in the meantime, which is not an option for vital components. It is suggested in Section 5 that about the only available strategy for dealing with the damage caused by major impacts, i.e. fast impacts by large objects, is to design vehicles in such a way that they contain structures that can be sacrificed, or can operate at a reduced level until the damage is repaired.

3.6 Group behaviour in animals

The behaviour of animals has long been a model for the performance of autonomous agents. As one possible implementation of an ageless vehicle would involve such agents, it is useful to consider possible models for their behaviour. Further discussions of animal group behaviours appear later in the section on intelligent systems.

Whales

Whales have very distinct cultures; different groups of the same species will have slightly different behaviours from other groups. They also display the ability to teach each other new ways of doing things: some teach each other new songs, others teach their young how to hunt. These behaviours add to the belief that whales have a high level of intelligence (Joordens, 2001). This discussion will include Orcas, or Killer Whales, even though these are not actually whales, because they exhibit similar behaviours.

Orcas develop specialized hunting techniques, which they teach to their young and which are unique to individual groups of whales (Alaska Sea Grant, 1996; Rendell and Whitehead, 2001). The adaptations apply to different types of prey and different techniques. Orcas that hunt relatively intelligent creatures, like seals or dolphins, do so with much greater stealth than those that hunt fish (Alaska Sea Grant, 1996). Some groups have developed a method of safely beaching themselves in order to catch seals on the shoreline, and they practice, and teach young, how to do this on a deserted beach before using it when hunting. Other whale hunting techniques involve acting for the benefit of the group ahead of the individual. For example, "bubble feeding" involves selected members of the pod surrounding prey with a wall of bubbles, allowing others to feed.

Whales have family structures. A group of whales, or a pod, may be either resident or itinerant, but one whale will remain with its family pod all its life (Spong, 1998). They communicate with each other using defined patterns that are individual to a pod (Spong, 1998; Spong, 2001).

Sources:
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Kangaroos

Kangaroos have an interesting social pattern. A community of kangaroos (a mob) tends to remain within one area of a few square kilometres. However, a mob is divided up into undefined subgroups of one to five kangaroos that intermingle and move around within their given area. A mob will tend to gather together only in times of danger or drought.

Mobs consist of about twenty kangaroos. Although a mob will remain within one area, younger kangaroos have been known to travel considerable distances. A mob will move out of an area if food becomes scarce, but generally return when feeding improves. Kangaroos are not territorial; the area covered by mobs often overlaps considerably with that of surrounding groups.

Sources:
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http://www.geocities.com/RainForest/Andes/1889/atoz/index.html;
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Ants

Ant colonies have the capability of self-organization, where small, simple, autonomous units will contribute together to achieve a set of goals. Nigel R. Franks from Bath University in the UK has been studying ‘Collective Problem Solving in Ants’ (http://www.bath.ac.uk/departments/BiolBioch/franks.htm):

> “Ant colonies embody all of the most important aspects of biological organisation. In simple terms they are more than the sum of their parts and they are robust flexible systems that are capable of self-repair. The fundamental advantage of ant colonies as experimental biological materials is that they can be quickly taken apart and rapidly and easily put together again. This is the reason why we study ant colonies rather than natural neural networks which exhibit similar capabilities but can be experimentally intractable.
>
> “We have developed mathematical models that show how the interaction of simple rules at the microscopic level (individual workers) can generate complexity at the macroscopic level (the colony). These mathematical models of self-organisation, often in the form of non-linear differential equations have been experimentally verified. We have shown that the ability of ants to generate spatial structures in their societies is critical to their organisation.”

Ants react collectively to changes in their environment. For example, worker Army ants, during swarming time, may link together to form an enormous living set of walls and chambers that *is* the nest, dissolving in the morning and reforming at a new location when necessary. The living structure will open and close ‘doors’ according to climate, the queen and younger ants being protected inside (http://www.myrmecology.org/mac/nest.htm).

The behaviour of ants has been studied extensively, and several ‘ant algorithms’ have been generated (http://evonet.dcs.napier.ac.uk/evoweb/site_tools/keywordlist5.10.html). This method of “swarm intelligence” has been applied in various areas, notably that of programming autonomous agents and in management:

> “Complexity-based tools will become increasingly important as the complexity of business grows, with growing connectivity. Their power lies not in their ability to solve complex business problems, many of which are theoretically insoluble, but in their ability to get closer to solutions than traditional approaches.
>
> “The famous travelling-salesman problem (finding the shortest route between a number of cities) is actually insoluble, because the number of computational steps needed to solve it grows faster than the number of cities. But ant-based models using artificial pheromones can get very close to an optimal route.” (Lloyd, 2001, http://money.telegraph.co.uk/money/main.jhtml?xml=%2Fmoney%2F2001%2F06%2F06%2Fcnantz06.xml).

Possible applications to intelligent systems

The herd behaviours of animal groups may apply to the performance and movement patterns of autonomous agents. An intelligent agent that exhibits learning behaviours may be modelled on the behaviour of the whale. The manner of dealing with energy supply requirements and dangers could be modelled on kangaroo or insect colonies. Repair mechanisms could work well when modelled on insect colonies.

None of these models actually cause problems in the implementation. Whether any particular analogy is applicable depends on the capabilities required of the autonomous agents.

3.7 Summary

Considerations of intelligent, or self-repairing, or regenerating systems invite consideration of biological analogues, since these are the only obvious examples of such capabilities. The performance of the human nervous system as an intelligent sensing, decision-making and control system is likely to remain a highly desirable objective for artificial systems for a long time. However, it is not necessarily the perfect solution for various reasons, a major one of which is its vulnerability to damage and an inability for self-repair of the central nervous system.

Similarly, many biological systems have developed extremely complicated and sophisticated mechanisms for repair, regeneration and recycling of tissue. While the precise mechanisms are almost certainly too complex to mirror in an ageless engineering structure, the principles of multi-stage repair, continuous material regeneration and the ability to regenerate lost or damaged components will need to be addressed in some form or other. Materials recycling processes, carried out at various levels in biological systems, will also be essential.

Group behaviour, including learning and emergent behaviour, in animals will be discussed further and its relevance emphasized in Section 6.

3.8 Further relevant areas for study in biology

There are many other areas of interest that are worth studying at a later date for their relevance to ageless vehicles. Examples include the following.

- **Trees:** trees and plants can cope with large amounts of damage and still recover. Trees are able to lose all their leaves (and hence their ability to produce energy) and still recover. Their protective outer layer (bark) is adaptive and regenerative. Trees are also the longest-lived organisms on the planet, and hence may be very useful as an analogy for an ageless vehicle.
- **Cell Structure and Interaction:** a possible model for the ageless vehicle is a composition of individual units. This may be comparable to the interaction of cells in a multicellular organism.

- **Sensing Mechanisms:** this is a very broad field that includes sight, hearing, touch, taste, smell, etc. Ideas have already been sought for sensors such as "artificial noses", hearing aids and cochlear implants. Molecular mechanisms for mechanical (touch) and pain (nociceptors) would make an interesting study.

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4. Materials and Structures

4.1 Introduction

The objective of this project is to examine conceptual issues involved in the development of intelligent health monitoring systems for ageless aerospace vehicles. While this requires that some consideration be given to agelessness of the sensing, communications and decision-making components of the vehicles, it does not specifically require work on the smart, repairable materials and structures that will form the basis of such vehicles. However, it is difficult and unwise to think about structural health monitoring without also thinking about the sorts of materials and structures that might be the subject of the monitoring.

Therefore, mainly as an educational exercise in the spirit of attempting to gain a flavour of the sorts of advanced materials and structures that ultimately might be incorporated into an ageless vehicle, an awareness activity with this aim has been maintained. This section documents some of the more interesting possibilities that have been investigated. Its purpose is to outline some existing options for materials and structures which are either capable of transforming their properties, especially shape, or repairing themselves in some fashion. It is not intended to be an exhaustive coverage, but instead attempts to cover generic technologies that may be useful on an ageless vehicle, regardless of whether appropriate materials for their implementation exist at present.

The next subsection discusses the various types of vehicles and the requirements each may make on materials and structures. Subsections 4.3 and 4.4 cover particular classes of materials and structures and include examples currently under development. In the final subsection (4.5), self-healing structures and materials are discussed. Some specific ideas for a new structural skin made from reconfigurable “intelligent” tiles, including aspects of regeneration, artificial surfaces that mimic natural processes, and a final section on computational aspects are described in the appendices to this report.

4.2 Material and structural requirements for different vehicle types

All types of vehicles are subjected to various dangers that depend on the environment in which they operate and the requirements of their mission. These include stresses, impact damage, and environmental degradation. They must all sense such damage and react appropriately (and/or learn to be proactive) to either repair or control the damage. They also have different structural requirements that depend on their environment and mission. As part of the analysis process, the Sensors Working Group selected four vehicle types for consideration. There are other possibilities, but these seem to provide an effective partition of the options. The general requirements of these vehicle types are listed in Section 2 as vehicle types A-D. They are presented below (in reverse order), with basic comments on additional materials implications.

D: Crewed aircraft

This type of vehicle is expected to take off, fly some distance in the Earth's atmosphere, and land again. The two most obvious requirements are for an aerodynamic external surface, and for life support for the crew and passengers. This type of craft will probably have the highest commercial sensitivity to cost, as well as the greatest ease of back-to-base maintenance. The system requirements are likely to focus on reliability, safety, and efficiency. There is less need for true agelessness due to the access to a base, but an integrated health monitoring system would offer advantages of reduced maintenance requirements, and reduced weight due to the reduced need for over-design. Detecting and controlling damage are the paramount concerns in order to ensure reliability and safety. Changing the aerodynamic surface during various flight stages (morphability) may be desirable to enhance performance efficiency. Such changes are not likely to involve changes to the mission profile (say growing new wings in order to carry a greater load) between maintenance accesses. The possibility of hypersonic flight may place additional requirements on the system.

C: Space shuttle, crewed

A shuttle has similar requirements to an aircraft. The major differences arise from the requirement for operation in a vacuum, and especially the ability to tolerate the extreme temperature stresses and ablation encountered during atmospheric re-entry. It is still likely that back-to-base maintenance will remain more economically attractive than complex self-repair. Continuous or ad hoc replacement of ablated material would reduce the need for, or the frequency of, maintenance cycles. It may be more attractive to perform such self-regeneration in space or on the ground (instead of during re-entry when the damage may occur) to simplify the stresses under which a replacement system must operate. It is possible that both ablation tolerance (regeneration) and morphability would be desirable. This is a rather demanding set of requirements, but a limited solution may be possible.

B: Orbital vehicle, crewed

Vehicles in permanent orbit have no need for aerodynamic capabilities, or for rapid changes in basic shape (morphability). They are not designed for re-entry so need no high-temperature ablation tolerance. They are in free fall, which reduces the stresses associated with their day-to-day motion. One new problem is that such structures cannot return to Earth for repair, so self-inspection and repair are more important. The close proximity to Earth[1] may make it possible to shuttle up a repair team for a major repair, rather than have all repair equipment on site. While mechanical stresses and external corrosion are reduced for a vehicle in orbit, the continuous wide range thermal cycling, solar and cosmic radiation, and impact damage from space debris and micrometeorites become major issues. Functional requirements of a vehicle in permanent orbit are likely to change, so some degree of (slow) functional plasticity is probably required.

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[1] It is conceivable that the vehicle may be in orbit about another astronomical object, negating the following comment.

A: Space vehicle, crewed (AC)

In many ways this is similar to the orbital vehicle. Some of the differences result from the likelihood of being too remote for shuttle-based repairs, and hence a greater dependence on self-repair. The availability of the crew makes some kind of human intervention in the repair process possible. Other issues include remoteness from planet-based scanning systems to compute debris and micrometeorite trajectories. This means the vehicle must take full responsibility for avoidance or protection strategies, in a continuously changing environment. If the vehicle's velocity is significantly higher than say orbital velocity, or particle velocity, the impact damage from space objects may be greater than for an orbital vehicle. This vehicle also may be subjected to significantly higher stresses during vehicle manœuvres. Depending on the duration of the mission, significant levels of functional plasticity may be required. It is possible to conceive of a multi-lifetime[2] mission where true agelessness is required.

A: Space vehicle, uncrewed (AU)

This is similar to the crewed space vehicle, but with some important differences. Removing the crew, and by assumption all other biological material, takes away some problems but adds others. There is no need for life support and protection, and possibly no need for pressurized cargo space. It may be possible for the system to tolerate higher accelerations and less radiation shielding. This allows for smaller, lighter, cheaper systems. Indeed it may make sense to use multiple or composite vehicles, and define mission survivability rather than vehicle survivability. The price for being uncrewed is the much higher degree of reliability that must be specified for the system, the much higher degree of autonomy required of the system, and especially the ability to deal with unforeseen problems. Strategies for reprocessing of damaged materials and even replacement of lost material may become important, but are outside the present scope.

Ageless Space Probe

The Voyager spacecraft are existing examples of vehicle type AU. They are generating scientific data and sending them to Earth many years after launch. There is an expectation that they may continue to return data out to 2020 or even beyond. They have had subsystem failures, which have resulted in use of spare equipment or reduced function. The concept of an ageless probe would require self-repairing, re-configurable subsystems, capable of dealing with unexpected events decades or even centuries after launch. The issues of functional plasticity and basic reliability are critical to such systems.

It seems likely that most deep-space vehicles in the foreseeable future, and certainly those that are sent on multi-decade missions and thus have the greatest requirements for agelessness, will be un-manned vehicles of type AU. These may be significantly smaller than current vehicles and incorporate evolvable capabilities (see, e.g. Toormarian, 2001, http://cism.jpl.nasa.gov/ehw/events/nasaeh01/papers/Toomarian.pdf).

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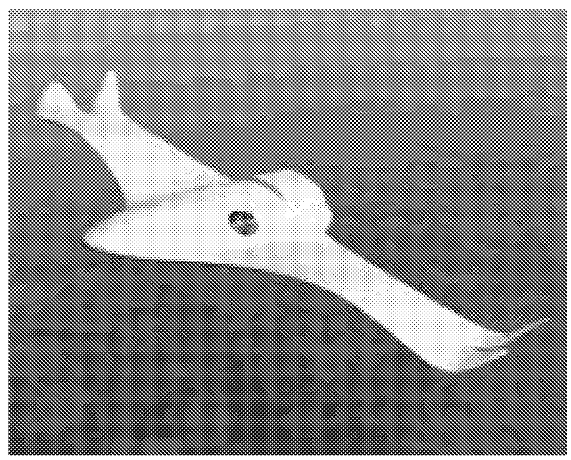
[2] Multiple human lifetimes.

NASA Morphcraft

The development of a vehicle with an adaptive structure capability is an area under active investigation by NASA. The concept of a variable geometry airframe that modifies its shape continuously to optimize its function is called a "morphcraft". The morphcraft changes wing shape (length, thickness, rake, etc.) to optimize efficiency at any speed, even splitting the wing tips to modify landing performance. The conception is of a vehicle with dynamic surfaces, and is far more complex than a swing-wing jet, which merely rotates the wing around a pivot. A computer-generated movie of a concept of such a craft may be found at:
http://www.spacescience.com/headlines/images/wings/morphing_med.mov.

The great complexity for an ageless morphcraft is the ability to provide a flexible surface and frame that is strong and reliable to implement, and autonomically repairable. At the present time, most proposals for such a structure have no clear mechanism for simple repair. Two proposals for such shape changes include "tensegrity" frames, which are open structures composed of beams under ideal compressive loads and cables under tension (see below for further descriptions). While the potential for shape transformation of such systems is high, it is not clear what kind of surface is proposed to provide an aerodynamic skin. Another proposal is for substances that change shape in response to external stimuli, such as shape memory alloys, or piezoelectric panels. While these structures are very interesting, they offer shape change on limited axes, or of limited variability. The "piezo" panels can warp and twist a surface, but seem unlikely to provide the flexibility required to change wing area.



Artist's impression of the morphcraft
(Image from NASA)

There is a press release from the Dryden Flight Research Centre at:
http://www.dfrc.nasa.gov/PAO/X-Press/stories/043001/new_morph.html
including quotes from Daniel S. Goldin

> "To convert to the low-speed configuration, the wings unsweep and increase in thickness and span to improve efficiency, … Instead of a vertical tail, the vehicle uses thrust vectoring. Adaptable wings are envisioned to have controllable, bone-like support structures covered by a flexible membrane with embedded muscle-like actuators. Embedded sensors provide health monitoring and control feedback.

> "As the vehicle morphs for landing, the wingtips split for tip vortex control and the wings lengthen for a shorter runway landing. A tail deploys providing noise shielding, increased lift and additional control…"

4.3 Materials

There are many aspects to be considered when assessing the suitability of self-repairing and flexible materials. They include the function to be performed by the material, the design of the component to achieve that function and the kinds of processes that enable the flexibility and repair mechanisms.

A major issue is that as materials are optimized for, say, low mass and high strength using some type of composite material, the mechanisms for failure become more complex, and the detection of damage and failure becomes more difficult. It is to be expected that as even more complex, morphing and self-repairing materials are used, the range of failure mechanisms will also increase. This increase in complexity requires commensurate checking, and indeed checks of the checking systems. A significant part of the operation of an ageless vehicle will be checking and cross-checking.

Technical requirements

The expectations of materials and structures which comprise an ageless aerospace vehicle are extremely broad reaching.

- Structural integrity, and durability.
- Functionality, ability and suitability for carrying out a mission.
- Efficiency with respect to energy and raw materials usage.
- Ability to adapt function and possibly form as missions evolve.
- Automated awareness of damage.
- Automated or autonomic repair or scheduling for repair of damage: both rapid damage-control processes, and slower, more permanent damage repair.

Subsystems

One possible division of vehicle subsystems, using a biological analogy, is into the following four subsystems.

- Skeleton (airframe) – the underlying basic shape defining structures, which are required to be controlled to a specific shape. The shape may be dynamic or fixed. If dynamic, the requirement for change might be slow (e.g. changing the instrument bay capacity) or fast (changing the wing shape to limit wing stress during flight).
- Muscles (actuators) – the controls that enable changes to the airframe, and operation of controls or instruments.
- Sense organs (optical/thermal/acoustic/chemical/mechanical sensors) – both to complete mission requirements and to detect functional and health requirements.

- Skin (airfoil/sealing) – to provide the aerodynamic surfaces needed to operate the vehicle in an atmosphere, and to provide sealing for pressurized or hermetic structures.

Characteristics of suitable materials

An ageless vehicle must be able to detect and repair damage to its structures. The sensing of damage is dealt with in the next section (Section 5), but the issues of self-healing and shape change should include consideration of the following areas.

- Repairable materials – capable of either or both immediate (temporary) or long-term (permanent) repair.
- Flexible materials – for morphing structures and skin.
- Active structures – as a core for the change of function.
- Self-replaceable structures.
- Self-renewing (growing) structures.
- Biological/technological composites.

Shape-changing materials (actuators)

There are a number of possible actuators that may be used in systems to control the shape of either tensegrity structures, or more conventional structures. This section will look at a few applications of actuators for aerospace systems.

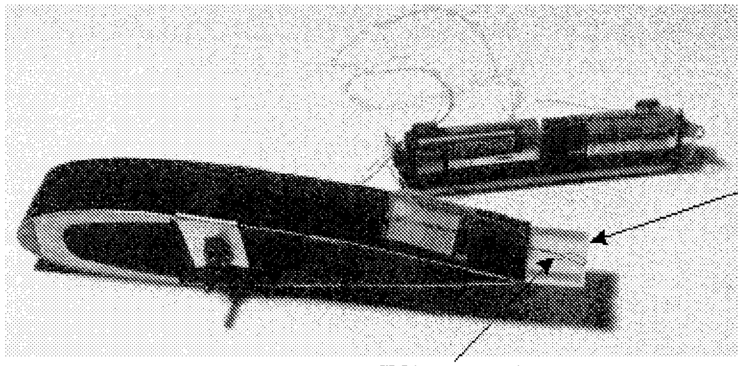
While there is great interest in these ideas, questions remain.

- Are the systems efficient enough to warrant long term use in cost and energy terms?
- The dynamic range of current actuators is limited. While wing flexing is quite possible, and has been demonstrated, a significant change in length to width of the wing's surface would be more difficult.
- The state of a system during power failure needs to be considered. Does the structure retain its rigidity or just become flexible? This may be an issue for highly flexible structures.

Some specific material types currently used as actuators include the following.

- *Shape memory alloys (SMAs)*

  Shape Memory Alloys (SMAs) are materials that return to a predetermined shape when heated through a crystallographic martensitic phase transformation. Below its transformation temperature an SMA may be easily formed from some original shape into any other shape. When it is heated to above its transition temperature its crystal structure transforms to cause it to return to its original shape. If the SMA encounters any resistance during this rearrangement it can generate considerable force. This phenomenon has found wide-ranging applications. One company, Continuum Dynamics Inc. has been using SMA actuator wires to control a small tab on the trailing edge of a helicopter rotor blade as shown below. The system is intended to actively damp vibration resonances (see http://www.continuum-dynamics.com/).



One of a number of introductions to different types of "smart" materials and applications can be seen at http://www.smartmaterials.info/materials/. In particular it shows variations on the same theme of helicopter blade resonance damping.

- *Piezoelectric materials and structures*

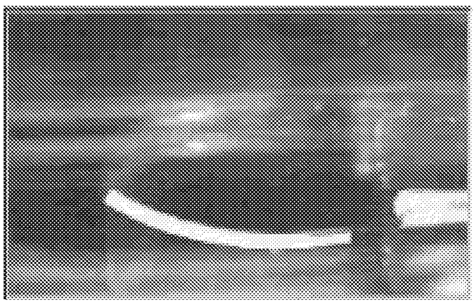
Piezoelectric materials have been used as actuators for many years, generally in the form of bimorphs or stacks. Simple piezoelectric structures (e.g. discs) can produce a large actuation force, but small strain. Bimorphs produce larger strains, but smaller forces. Recently, more complex structures, generally based on bimorphs, have been devised to produce much larger strains.

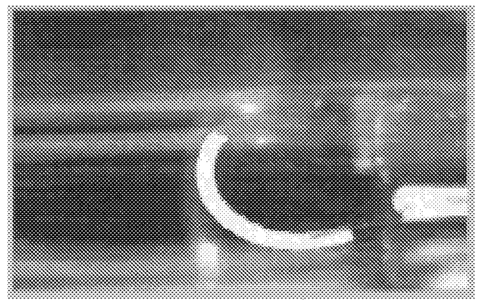
NASA is developing laminates containing piezoelectric sheets that bend when a voltage is applied. They can also be used as sensors, generating a voltage when pressure is applied. Thus the same unit may act as both sensor and actuator. Flexible wings, with embedded arrays of piezoelectric sheets in a laminated structure, have been proposed. See http://science.nasa.gov/headlines/y2001/ast01mar_1.htm, http://www.nttc.edu/techmart/technology.asp?technology_id=10, http://www.darpa.mil/dso/thrust/md/smartmat/programs.html, http://www-personal.engin.umich.edu/~dibrei/smartmat/.

- *Electro-active polymers (EAPs)*

In recent years there has been considerable research on ionic or electro-active polymers. These have the ability to produce larger displacements than typical piezoceramics, although the forces they can exert are low. EAPs may be electronic or ionic, with the latter conducting via ion diffusion. Like the piezoceramic transducers, electro-active polymers can be used as both sensors and actuators. Some applications are "artificial muscles" and polymer sensors. There is quite a large international community working on the development and application of EAPs, including the Intelligent Polymer Research Institute at the University of Wollongong, NSW (http://www.uow.edu.au/science/research/ipri/contents.html), which is working with CSIRO on the development of smart textiles.

Another group working in this area is the Artificial Muscle Research Institute at the University of New Mexico, which is developing elastomeric "muscles" which can be electrically flexed. They have numerous movies of some experimental systems they have developed. Their web site is http://www.unm.edu/~amri/. A couple of pictures extracted from one movie show one type of "artificial muscle" reacting to an electrical stimulus.





Other movies show more complex structures of a similar flexing type, and different types of materials that are electro-active in a longitudinal sense. There are a growing number of companies with products in this area. See, for example http://www.biomimetic.com/.

NASA also has a site with a large collection of papers, and some interesting pictures, on the topic of electro-active polymer actuators at http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/aa-hp.htm.

- *Giant magnetostrictive materials*

These materials (e.g. Terfenol-D) experience a change in length in magnetic fields. While not having the high frequency response of piezoceramics, magnetostrictive materials can produce much larger strains, of the order of 1000 ppm, and are capable of producing large forces. In general magnetostrictive materials are mechanically biased with a compressive pre-load. They have been used in devices such as inchworm motors (see http://sbir.gsfc.nasa.gov/SBIR/successes/ss/9-062text.html).

4.4 Structures

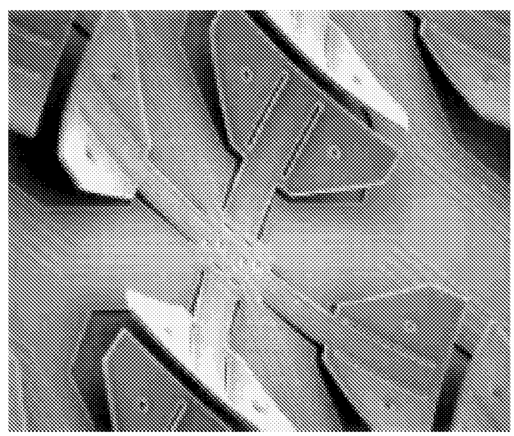
This subsection is concerned with structures or types of structures that are capable of adaptation to improve performance in response to various conditions. Active surfaces, in which the surface properties can be modified to perform particular functions, are one such class of structures that are outlined here. Another is the use of reconfigurable modules ("tiles") to form a structure or surface. These might share some of the characteristics of an active surface, but would be expected to have a wider range of capabilities. A third type of adaptable structure described here is a broad range of structures known as "tensegrity" structures.

Active surfaces

There are many materials that have active surface properties, but could not strictly be called flexible in the short term sense, but nevertheless have dynamic characteristics that may be of value. Two, with very different characteristics, are briefly covered below.

a) *Micro-cilia for surface guidance*
A press release from the University of Washington describes a process for developing a surface that can cause objects in contact with the surface to move laterally across the surface, using locomotion similar to that produced by cilia on the surfaces of cells. The report and the picture below can be seen at http://www.washington.edu/newsroom/news/2001archive/12-01archive/k123101.html.

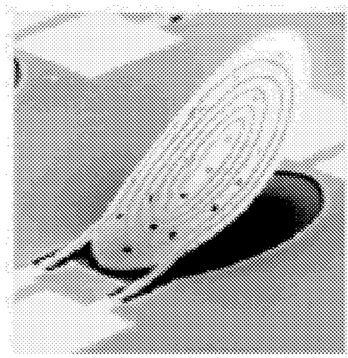
Beds of thousands of tiny pulsating artificial "hairs" can provide a precise method for steering small satellites to docking stations on larger vessels … The technique is inspired by biology, patterned after the action of the small hairs, or cilia, that line the windpipe and keep it clear of mucus. It could come into wide use in future space missions as technicians begin to deploy swarms of "pico-satellites" – spacecraft small enough to fit in the palm of one's hand – to do maintenance, repair and observation work for larger satellites or space stations …



In creating the devices, Kovacs and Suh of Stanford University deposited layers of a polymer on a flat silicon plate and then, using micro-machining processes, carved out units, or cells, containing four cilia each. The cilia are just 0.5 millimeters (two hundreths of an inch) tall, and each cell resembles a diminutive four-leaf clover. Each cilium contains a titanium-tungsten heating element. When at rest, the cilia curve up and away from the silicon plate, but when current is applied to the heating element the cilia are forced to flatten. By turning cilia facing the same direction on and off in sequence, Bohringer can prompt them to act like thousands of tiny fingers that move in pulsating waves to nudge objects in any of eight directions …

The one downside, he said, was that the process used more electricity than he would have liked. However, he is confident that can be addressed with some design changes.

While these structures are not flexible in the sense implied by morphability, there is a significant potential in changing configurations and positions of surface structures, and objects. It is interesting that an array of simple and tiny objects can collaborate to produce a complex motion in a much larger object.



b) *Distributed MEMS for aerodynamic control*
A.A. Berlin from Xerox and K.J. Gabriel of DARPA have developed the idea of MEMS microflaps which could be laid out as a massive array forming an active surface across the surface of a wing. Their paper "Distributed MEMS: New Challenges for Computation" (IEEE Computational Science and Engineering, Jan/Mar 1997) describes "tiny flaps" embedded in the surface of an aircraft wing, which could, for instance, reduce drag by sensing vortices and interacting with them (http://ho.seas.ucla.edu).

<u>*Reconfigurable tiles*</u>

One limitation of all of the examples above is that there is no particular consideration given to means of self-repair. Also, as was noted when looking at types of vehicles earlier, not all vehicle types have a need for rapid morphability. Even so, for such vehicles there is still likely to be a need for functional plasticity or reconfiguration.

One possible method of achieving this is to make the vehicle out of reconfigurable sub-components[3]. The International Space Station is an example of this on the large scale, in that it is composed of modular sections. But why not do this at a much smaller scale? One mechanism for doing this is to build structures from arrays of tiles or blocks.

There are several positive outcomes from such a design.

- A limited number of sub-components can be assembled into a wide variety of structures.
- An existing structure can be disassembled and reassembled in quite a different configuration as a mission evolves.
- A damaged tile or block (or even a large number of them) can be replaced quickly, and either repaired or recycled or, if very badly damaged, discarded.
- The subsections have fixed joining points for assembly, which makes possible fixed mechanisms for interconnection of the tiles or blocks, both physically and in a communications sense.

[3] Like ®Lego or ®Meccano.

In essence such a design has a significant degree of flexibility, and repairability. The negative consequences include the following.

- A structure made of small tiles or blocks is likely to cost more that a structure made of larger purpose-built components.
- Because of a requirement for flexibility of assembly and function, the tiles or blocks are likely to be over-designed for many simple applications.
- A system, made of many components, may have many more possible failure points than one made of fewer parts.

This means that to be successful a tile-based system must value the flexibility and reparability options over the initial cost.

A proposal for such a tile-based system is presented in Appendix A4.1. It is designed to provide not only flexible and repairable sub-structures, but also automated self-assembly and replacement, as well as integrated sensing and communications.

There is a significant question of complexity versus reliability for such systems. Is a complex self-repairing system more or less reliable than a simpler irreparable system? It would seem that, at least in biological systems, complex self-healing systems are superior.

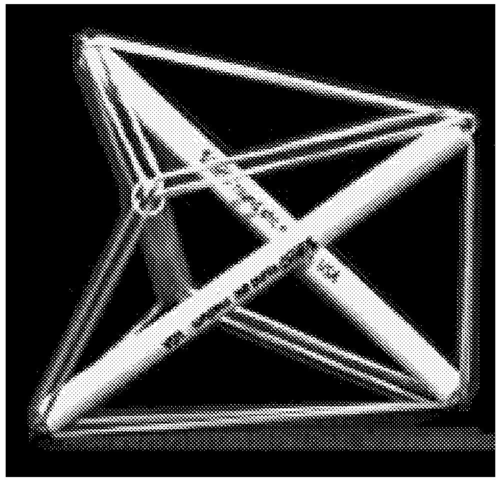
Tensegrity structures

Tensegrity is a composite word for "tensional integrity", attributed to R. Buckminster Fuller, to describe a stable three-dimensional structure which transfers locally applied forces in the structure, sharing them across the whole structure, consisting of members under tension that are contiguous and members under compression that are not. The original structures were invented by artist K. Snelson, whose work is fascinating from both engineering and artistic viewpoints.

A common class of tensegrity structures consists of interconnected rods and strings. The rods are under compression and the strings under tension. As the rods are connected only by strings, no bending force can be applied to the rods, thus removing the major source of failure during compression. String tension gives the structure its rigidity. The systems are operated with initial tension (pre-stress) applied to the strings.

Advantages of tensegrity structures include:

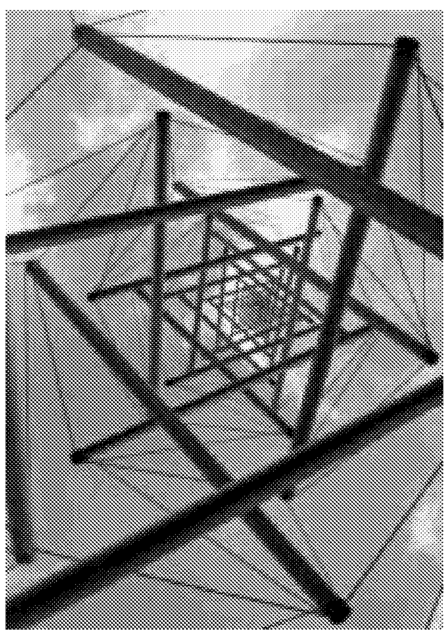
- high stiffness and strength to weight ratios;
- large potential shape changes, if either the bars or the strings have variable length;
- no reversal of compression to tension, so no hysteresis or friction;
- all forces on members are axial;
- easy to model numerically.



A simple tensegrity structure made from ball-point pens and elastic bands.

Disadvantages of these structures include:

- the need for fairly complex control structures to vary bar or string length;
- the potentially catastrophic transition in strength if external loadings cause one or more strings to lose tension.



View from inside a tensegrity sculpture by K. Snelson

The particular interest of the tensegrities for aerospace structures comes from the very high strength to weight ratio, and the large geometrical changes that are possible by changing the lengths of the rods and strings. Of particular interest is the fact that the structures are stable over a wide range of shapes, and that the energy required to move from one shape to another is fairly low.

A couple of systems of interest are:

- a mechanical system using tensegrity prisms for large shape changes in physical structures at UCSD, Mechanical and Aerospace Engineering, illustrating the complexities involved in building such systems, (see http://www.mae.ucsd.edu/research/reskelton/struclab/bars.html);
- tensegrity structures designed to vary the shape of aircraft wings, (see http://www.darpa.mil/dso/thrust/md/chap/briefings/timchap2000day2/tensegrity_skelton.pdf).

A significant issue that does not seem to have been addressed fully is the difficulty of defining an aerodynamic surface (skin) that is flexible enough to change shape, and tough enough to survive the rigours of commercial flight. A proposal is offered in Appendix 4.3.4 for the use of a scaled (or feathered) surface, which allows a significant degree of shape change, while still providing an aerodynamic surface.

Biological tensegrity
The issue of flexible skin requirements leads to the investigation of biological systems. The article by Donald Ingber in Scientific American (pp 30-39, January 1998), entitled "The Architecture of Life" discusses some issues concerning the shapes of cells, and how they recognise a need for change and respond.
http://www.sciam.com/1998/0198issue/0198ingber.html
Some extracts are transcribed below.

> *"From Skeleton to Cytoskeleton*
> What does tensegrity have to do with the human body? The principles of tensegrity apply at essentially every detectable size scale in the body. At the macroscopic level, the 206 bones that constitute our skeleton are pulled up against the force of gravity and stabilized in a vertical form by the pull of tensile muscles, tendons and ligaments (similar to the cables in Snelson's sculptures). In other words, in the complex tensegrity structure inside every one of us, bones are the compression struts, and muscles, tendons and ligaments are the tension-bearing members. At the other end of the scale, proteins and other key molecules in the body also stabilize themselves through the principles of tensegrity. My own interest lies in between these two extremes, at the cellular level.
>
> As a graduate student working with James D. Jamieson at Yale, I focused on how the components of biological systems - especially of cells - interacted mechanically. At this time, in the late 1970s, biologists generally viewed the cell as a viscous fluid or gel surrounded by a membrane, much like a balloon filled with molasses. Cells were known to contain an internal framework, or cytoskeleton, composed of three different types of molecular protein polymers,

known as microfilaments, intermediate filaments and microtubules. But their role in controlling cell shape was poorly understood…

How Mechanics Controls Biochemistry

… By simply modifying the shape of the cell, they could switch cells between different genetic programs. Cells that spread flat became more likely to divide, whereas round cells that were prevented from spreading activated a death program known as apoptosis. When cells were neither too extended nor too retracted, they neither divided nor died. Instead they differentiated themselves in a tissue-specific manner: capillary cells formed hollow capillary tubes; liver cells secreted proteins that the liver normally supplies to the blood; and so on.

Thus, mechanical restructuring of the cell and cytoskeleton apparently tells the cell what to do. Very flat cells, with their cytoskeletons stretched, sense that more cells are needed to cover the surrounding substrate – as in wound repair – and that cell division is needed. Rounding indicates that too many cells are competing for space on the matrix and that cells are proliferating too much; some must die to prevent tumor formation. In between these two extremes, normal tissue function is established and maintained. Understanding how this switching occurs could lead to new approaches to cancer therapy and tissue repair and perhaps even to the creation of artificial-tissue replacements…

Making Cells Do the Twist

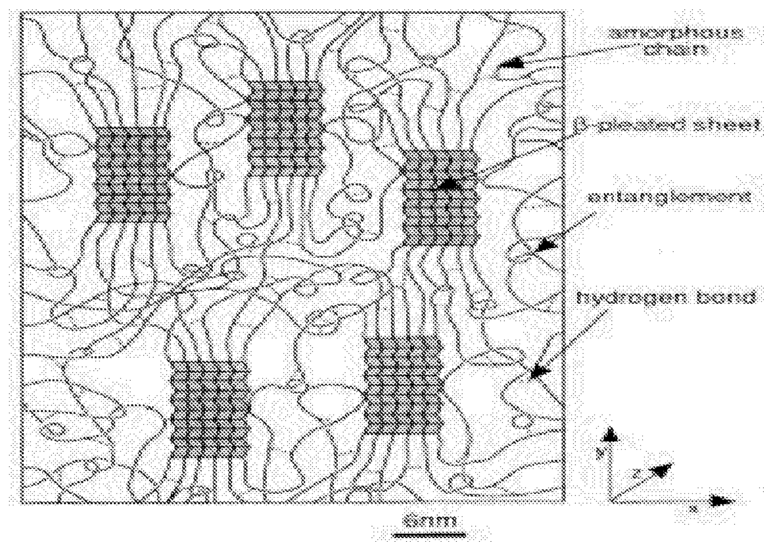
The next level up in the hierarchy of self-assembly is the formation of tissues, which are created from the joining of cells to one another and to their extracellular matrix. One emergent property of tissues is how they behave mechanically. Many different types of tissue, including muscle, cartilage, blood vessels and skin, exhibit a response known as linear stiffening. If you pull on your skin, for example, you will feel the resistance increase as you tug harder. An increasing external force is met with increasing resistance. Recent studies show that even isolated molecules, such as DNA, exhibit linear stiffening, yet until we examined this phenomenon in the context of tensegrity, there was no mechanical or mathematical explanation for this behavior.

In 1993 my co-worker Ning Wang, working with James P. Butler of the Harvard School of Public Health, developed a device that allowed us to twist individual molecules on the surface membrane of living cells while simultaneously measuring the cellular response. We found that when we increased the stress applied to integrins (molecules that go through the cell's membrane and link the extracellular matrix to the internal cytoskeleton), the cells responded by becoming stiffer and stiffer – just as whole tissues do. Furthermore, living cells could be made stiff or flexible by varying the pre-stress in the cytoskeleton by changing, for example, the tension in contractile microfilaments…"

Cell structures have been described in great detail elsewhere. See for instance, http://www.accd.edu/sac/biology/ratorres/printouts/psm11c.htm.

In “An Introduction to the Mechanics of Tensegrity Structures”, by R.E. Skelton et al. (in “Handbook on Mechanical Systems Design”), there is some material on the underlying structure of spider silk. An extract follows.

> “The figure shows a rendition of spider fiber, where amino acids of two types have formed hard β-pleated sheets that can take compression, and thin strands that take tension… The β-pleated sheets are discontinuous, and the tension members form a continuous network. Hence, the nanostructure of the spider fiber is a tensegrity structure. Nature’s endorsement of tensegrity structures warrants our attention because per unit mass, the spider fiber is the strongest natural fiber.”



4.5 Self-healing materials and structures

Limits on repairability

Any system is going to be limited in the rate at which it can deal with damage. A vehicle may be destroyed before it has time to heal itself. A new wing cannot be re-grown instantly if blown off – it may take some time to recover full function even in an extremely flexible system. A temporary, fast response to mitigate further damage may be the first step in a staged recovery from damage. Under some circumstances a vehicle may be permanently, partially disabled, but may be capable of completing its mission with reduced capacity or effectiveness. This is likely to be more valuable than a simple shut down. This issue is discussed further in Section 5.

Technical solutions

One interesting and practical example of a simple self-repairing material is given by White et al.[4]. This paper describes a fibre-reinforced polymer composite that has tiny microcapsules of a polymer precursor. The composite also contains a polymerization catalyst. If a crack penetrates a microcapsule, the polymer precursor comes in contact with the catalyst and the crack is filled and locked. The paper reports about 75% recovery of load tolerance after "healing".

Clearly there are limitations. Repeated damage results in progressive weakening, and eventually the system must fail.

> "We expect that the field of self-healing, although still in its infancy, will evolve beyond the method presented here until true biomimetic healing is achieved by incorporating a circulatory system that continuously transports the necessary chemicals and building blocks of healing to the site of damage" (White et al.)

For truly ageless systems the mechanisms involved must not just heal the crack, but restore the damaged material to its original state.

Another limitation of this material is how it would respond to a large crack that requires large volume filling very quickly? One possible solution is discussed in Appendix A4.3.2 of this report: a layer of pressurized epoxy foam, that oozes, expands and sets on exposure to some initiator. Further, if the skin is a flow/lift surface, there must be some mechanism to control surface texture, such as bark peeling (internal control), or surface abrading (external agent).

Biological compatibility

The existence of the biological mechanisms for "agelessness", and their high levels of sophistication compared to present technical proposals, raises a question of using either natural or engineered bio-materials as part of an ageless vehicle.

Interestingly, much of the experience of biological/technological compatibility comes from the attempt to do the opposite of what is being proposed here. The typical motivator is the attempt to use some technological intervention to allow replacement of some body part that does not heal on its own. The demand is for a solution as soon as possible to preserve or enhance life.

In contrast, what is being sought for the ageless vehicles is a long term solution that may involve biological or biologically inspired systems to provide agelessness for a technological system.

In spite of the differences, some interesting issues of biological compatibility are common to the two approaches. These go beyond ensuring that inserted technology is not rejected through pathological reactions. What is critical is to be able to integrate

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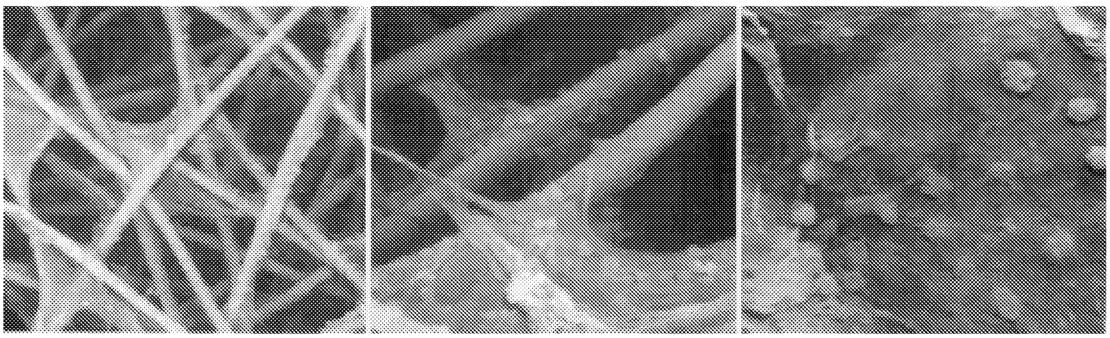
[4] S.R. White et al "Autonomic healing of polymer composites", in Nature Vol 409, pp 794-797, 15 February 2001. See also comments by R.P.Wool "A material fix" on pp 773-774 of the same issue.

biological systems into, or onto, technological substrates. The biological systems have to grow and function as required by the technology, not just randomly.

This report will consider only a couple of indicative projects. The first is work done by J.P. Vacanti of Harvard Medical School, on engineered substrates, which are used to define the shape of a desired tissue part and which support the growth of biological cells.



The cells grow over and through the substrate, gradually filling the spaces in its scaffolding, to form a shaped tissue structure. The scaffold eventually biodegrades, leaving only living tissue. The work is discussed in a review article "Artificial Organs" in the September 1995 issue of Scientific American (pp 100-103). The pictures above, from that article, show the cells growing on the scaffold.

The picture at the right shows the growth of an ear-like structure on the back of a laboratory mouse. The ear-shaped scaffold was implanted, and progressively filled with cells. The long-term aim would be to re-grow an "artificial ear" for a patient who had lost one due to injury.

The second project comes from work done at MIT and NYU where a biomaterial has been developed to support living nerve cells. On this peptide-based scaffold, neurons grow fibers to communicate with each other and establish functional synapses. This work is intended to allow the development of structures that encourage re-growth of damaged nerves. See http://web.mit.edu/newsoffice/nr/2000/biomaterial.html.

While these projects are both intended to allow re-growth of biological tissues, the basic principles may be applicable to the growth of biological or hybrid structures on technological substrates.

5. Sensors

5.1 Introduction

Our earlier report for this project (CTIP, 2002) considered and listed the types of threats to which an aerospace vehicle is likely to be subject, the quantities that could be measured (measurands) to detect those threats or their consequences, and it discussed a number of issues related to sensors and integrated sensing systems for vehicle health monitoring. This work has been continued by considering in more detail the threats to the different functional components of specific vehicle types, with the aim of arriving at a set of priorities for the various measurands and sensor types for different vehicles and environments. A more detailed investigation was carried out of the threats presented by the space environment (referred to as external threats in Report 1 (CTIP, 2002)), using information obtained from NASA and other organizations. This work is not yet complete. So far only the space vehicle (defined as vehicle type A in Section 2 of this report) has been considered in any detail, but others will be studied during later phases of the project. The results of the work completed so far are reported in this section.

Significant issues identified in Report 1 (CTIP, 2002) included the following.

- The requirements for the sensing and response system for an ageless vehicle are complex: measurements must be made of a large variety of mechanical, chemical and electrical quantities, at a wide range of temporal and spatial scales. To this can be added a broad range of measurement conditions and locations. It will be desirable to simplify and modularize the sensing system.
- A number of quantities require rapid detection and a rapid response. These are associated with threats that could lead to catastrophic results for the vehicle or its occupants. These quantities should be detected by sensors that are continually in position and in operation: they should be either integral to the material or embedded in the structure, or remote but fixed.
- Measurements that do not require rapid response could be carried out with movable sensors, perhaps mounted on autonomous agents, and may employ active measurement techniques.
- An integrated sensing system might have distinguishably different supervisory and repair/response roles. It will probably be desirable for knowledge of threats and damage to be shared more widely, even if repair is carried out autonomically and locally.
- The system will need to distinguish structural material damage from sensor or system malfunction: a lack of information from a sensor may indicate damage to the host material, but it may not.
- Information loss and software reliability are major issues for agelessness.
- Finally, and importantly, the choice of sensing methods and measurement techniques may well be influenced by considerations relating to the data processing, communication and decision-making aspects of the system. It is essential that a holistic approach be taken to the development of basic concepts in all of these areas.

The general structure of this section is as follows. In the next sub-section (5.2) some general issues raised during the course of the work are discussed. Following this the threats presented by the space environment are outlined, and general strategies for dealing with them proposed. A similarly general discussion of the internal threats to a vehicle, its sub-systems or passengers follows in sub-section 5.4. The types of responses to these threats or their consequences (damage) are outlined in 5.5. The methodology and results of the sensor and measurand prioritization exercise are given in sub-sections 5.6 and 5.7. Sub-section 5.8 describes some work in other institutions that is concerned with embedded sensors and real-time detection of damage. Finally, a recommendation is made regarding the types of sensors that could be appropriate for the concept demonstrator that is to be developed in the next phases of this project.

5.2 Issues related to the sensing system

Continuous monitoring vs. evaluation of accumulated damage

Most conventional non-destructive evaluation (NDE) techniques and practices involve regular inspections of structures or materials at pre-determined intervals, with the aim of detecting damage that has accumulated during the interval. In some cases the interval between inspections is determined by performance of the structure, e.g. according to fuel consumption, the appearance of visible cracks, or in more sophisticated situations by the results of condition monitoring measurements. In other cases, particularly where safety is critical, the intervals are prescribed periods of time or operation. In general, active measurements are performed: the material is excited by some form of energy, and the response to the excitation is measured. Common excitation methods include X-rays, ultrasound, vibration and optical radiation. Usually the excitation and sensing are carried out with a small number of portable transducers that are positioned and operated under the control of the inspector.

Integrated structural monitoring systems can mimic this conventional mode of operation, i.e. the measurement of accumulated damage at intervals, but using embedded sensors. This has advantages in inspectability and in inspection time: it is no longer necessary to design the structure in such a way that an inspector (human or robotic) can gain access to all inspection points. It also has disadvantages related to long-term reliability (see below), adaptability and it is inherently reactive and has obvious limitations in its ability to deal with unexpected damage events that require a rapid response.

The interest here is with systems capable of continuous monitoring to provide real-time detection of damage using large arrays of sensors embedded in the vehicle structure. The requirements for sensors, measurement techniques and data processing methods are very different from those employed in conventional NDE. This presents opportunities to seek novel methods and strategies for detecting and evaluating damage. Event detection (e.g. an impact or crack) and damage assessment may be carried out with the same or different sensors; embedded sensors may be used in combination with movable sensors (which could be mounted on autonomous agents); embedded sensors may be used in adaptively reconfigurable arrays or in synthetic arrays; the integrity of the sensor network itself may be used to detect and assess the extent of damage; multi-modal sensing of a damage event may provide valuable information about the nature and cause of the event.

The main advantages of continuous monitoring, however, are expected to lie in the ability to detect precursors to damaging events, which in many cases will allow major damage to be averted, the ability to take early action to minimize the consequences of damage, and the information provided by real-time monitoring to understand the causes of a damaging event so that similar events can be averted in the future.

Some requirements of sensors for continuous monitoring

The functions of a continuous monitoring system are to record conditions leading up to a damage event (and to initiate action, if possible, to avert or minimize the damage), to record, identify and locate the damage event, and to provide some information to assist with evaluation of the nature and extent of the damage. Damaging events can occur very rapidly in some cases, and damage can propagate rapidly. Therefore, depending on the nature of the measurand, sensors and their interface electronics must have high bandwidths and fast sampling rates.

However, damage can also accumulate slowly. For example, fatigue, wear, erosion and other material degradation mechanisms may develop from the accumulation of many small events over days, weeks or years. Some of the small events that lead to slowly accumulating damage, such as impacts by micrometeoroids or fatigue-induced microcracking, may be individually detectable, but others may not. It is important that these forms of slowly accumulating damage are detected and monitored from an early stage. Materials that continually self-regenerate may eventually be developed, and this may relieve the sensing system of the responsibility of initiating repair, but the supervisory system would surely want to know about rates of degradation and changes in them.

Real-time detection of rapidly occurring events requires sensors that are in continuous operation. This is a very different requirement to that of many conventional NDE methods. It favours the use of passive sensors, though they may be used in conjunction with an excitation source (e.g. an optical imaging sensor may require a source of illumination). In a number of cases this will require the development of new types of sensors. For example, most current chemical sensors, or at least those that selectively detect individual species, are batch sensors. Chemical sensors based on spectroscopic techniques (e.g. mass, optical) may be suitable.

Similarly, continuous real-time detection of damage favours the use of fixed sensors embedded in or permanently attached to the structure. Mobile sensors (and/or excitation sources), possibly mounted on autonomous agents, may be useful for assessment of damage after the event or of accumulated damage, but are expected to be less appropriate for primary event detection.

On the basis of these considerations it is expected that a continuous vehicle health monitoring system will consist largely of passive embedded sensors.

Long-term reliability of the sensing system

One of the major issues for systems of embedded sensors will be long-term reliability. The sensing system must be less prone to damage (or at least no more prone) than the structure in which it is embedded. If this cannot be guaranteed, and it probably never can, then it must be possible to test the system and repair it when necessary. Thus, along with materials capable of self-repair, there will be an equally important requirement for self-repairing sensing systems. Repair of the central and peripheral nervous systems in mammals was outlined in Section 3. There are mechanisms that inhibit the repair of the central nervous system, possibly because such processes themselves would be risky and unreliable. This may be an indication of the complexity of the task of developing a sensing system with the level of reliability required.

It is important to recognize that calibration is a significant issue for sensor reliability. Changes in the sensitivity of sensors can result from changes in ambient conditions (e.g. temperature, pressure) but if these conditions are measured corrections can be made where necessary. However, sensitivity variations can also result from various forms of material degradation or change within the sensor, perhaps due to thermal or mechanical cycling (fatigue), radiation, atomic or molecular diffusion, etc. All sensors require periodic calibration: the frequency with which this is required will depend on the particular sensor, its operating environment and the accuracy requirement for the particular measurand.

5.3 External threats: the space environment

An outline of the more important effects the space environment has on spacecraft may be found in NASA documents such as Reference Publication 1350 (NASA, 1994). The sources of these effects may be categorized and are listed below.

i. Atmospheric density and composition – Corrosion and materials degradation caused by atomic oxygen in particular; drag/decay; interferes with sensors, guidance, navigation and control (GNC) systems; increases surface contamination.
ii. Solar radiation – Influences solar panel design and power allocation; contributes to thermally induced fatigue. Spacecraft need passive and active thermal control.
iii. Plasma – Ionospheric and mesospheric plasma cause EMI, charging, heating and therefore influences power system design, and threatens most electronics.
iv. Meteoroids, debris – Collisions have wide-ranging effects, from catastrophic impacts with large objects to solar panel damage, surface erosion and contamination. The tracking of threats, avoidance of collisions and shielding are requisites.
v. Solar – Large fluxes at radio to X-ray frequencies affect the thermal environment, the surrounding plasma and meteoroid densities, and ionization levels, all of which affect the spacecraft. Large variations in the solar activity need monitoring and predicting.

vi. Ionization – Charged particle flux, cosmic rays, solar flare particles (mainly protons) all necessitate protection for electronics and humans. It can also cause degradation and failure of avionics and materials.
vii. Geomagnetic fields – Influence the motion of particles within the Earth's orbital environment, cause currents in large structures, and affects GNC systems.
viii. Gravitation – Influences orbital mechanics, fuel consumption, etc.
ix. Mesosphere – Affects GNC on re-entry, degrades materials.

Of particular concern are the general areas of the effects of atomic oxygen, solar radiation, charged particles from various sources, and impacts. Important mitigation strategies for the effects of atomic oxygen would be to include sensors to monitor charge build-up (possibly thick-film sensors), to monitor material degradation, and to choose appropriate materials to minimize effects such as charge accumulation, spacecraft glow, etc.

Impacts with micrometeoroids and orbital debris are a major area of concern. Appendix A5.1 contains a summary of relevant information obtained from a number of sources. The average velocity of collisions is of the order of 10 km/s. General strategies for mitigation of collision damage based on object or particle size and mass are as follows.

- Particles less than ~1 mm diameter and less than ~1 mg in mass. Impacts relatively frequent. Monitor surface degradation, particularly on poorly protected surfaces (e.g. windows, solar panels).
- Particles between ~1 mm and ~1 cm diameter, or between ~1 mg and 1 g in mass. Monitor individual impacts and evaluate damage. Well-designed shielding is generally effective in minimizing damage.
- Particles between ~1 cm and ~10 cm in diameter (~1 g to ~ 1 kg). These present a difficult problem. They can cause significant damage, but are too small for effective detection or tracking. Need to monitor impacts and evaluate damage. Protection is incorporated in spacecraft design: redundant sub-systems, frangible shielding, pressure vessel isolation, maximum physical separation of redundant components and paths of electrical and fluid lines, etc. Spacecraft flight attitude is also important.
- Objects greater than ~ 10 cm in diameter and greater than ~1 kg in mass. These are likely to be fatal, or at least cause major damage to a vehicle. Fortunately there are very few of these objects, so the probability of collision is very small. The only strategies are early detection (objects in this range may be tracked in low Earth orbit by ground-based radar, but the minimum detectable size increases with altitude) and/or the use of vehicles designed with major sections that can be sacrificed if necessary.

Ionizing radiation, from both solar and galactic sources, is a concern from the points of view of human health (and the health of other biological material) and vehicle health. Electronic systems are particularly vulnerable to high-energy particle radiation, and may become more so as typical gate structures in semiconductor devices become smaller. Appendix A5.2 summarizes information about solar and galactic particle radiation threats. High-energy photons (from UV to X-rays) are of course also major threats, particularly within the solar system. Monitoring solar cycles, both daily and long-term, is desirable so that shields may be deployed to protect (normally) exposed and sensitive instrumentation from higher solar intensities.

Active and passive regulation of the temperature of spacecraft components occurs now, but the avoidance of rapid temperature fluctuations through the use of continual, fast, probably embedded sensors would facilitate these techniques. Extreme thermal environments should be avoided.

Charging of spacecraft, due to plasma, solar or other ionization effects, can cause failure in electronic components and a host of other consequential effects such as material degradation, surface erosion and contamination. While the design of electronics influences the way in which components cope with charge accumulation, a network of sensors as well as active grounding may ameliorate these effects. The measurement of material and surface properties is also important.

The networking and interpretation of the outputs of several sensors, which are monitoring separate phenomena that may combine in some non-linear way to accelerate one or several damage mechanisms, is one example of a "smart" sensing system.

5.4 Internal threats

Internal threats are those generated within the vehicle, or indirectly due to the external environment. They were listed in some detail in Report 1 (CTIP, 2002), and reference should be made to that report. They include threats, or the consequences of other threats, to the following.

1. The materials from which the vehicle is fabricated.
   - Mechanical failure of materials (fracture, debonding, cracking, …).
   - Material degradation at surfaces (wear, erosion, corrosion, …).
   - Bulk material degradation (fatigue, creep, adhesion, radiation damage, …).

2. The fuel and propulsion system.
   - Engine failure (which may be due to material failure).
   - Fuel leaks, contamination.

3. The energy and power systems (non-propulsion).
   - Generators (solar panels, nuclear, thermoelectric, …).
   - Batteries, storage devices.
   - Energy distribution system (wiring, insulation failures).

4. Electronic systems.
   - GNC (guidance, navigation & control) systems.
   - Communications systems (internal and external).

   - Sensing and supervisory systems.

5. Life support systems.
   - Atmosphere (pressure, temperature, composition/contamination, explosive mixtures, …).
   - Water (quantity, purity, contamination), food.
   - Health systems (sensing, monitoring, treatment, …).
   - Waste disposal, recycling.
   - Light, sound.
   - Entertainment.

These threats, and means of detecting and evaluating them, will be discussed in the following subsections of this report.

5.5 Responses to threats or their consequences

The response to the detection of a threat, or to the consequence of a threat, may be a permanent (ideal) response, or a temporary response that is essentially a means of increasing the time available to achieve an ideal response.

Ideal responses are to avoid the threat or its consequences, or to permanently and effectively repair the damage. Avoidance may take various forms. In the case of collisions with objects, it would include the detection of an approaching object followed by the taking of evasive action, the destruction or deflection of the object, or the deployment of a shield. It can also take the form of detection and correction of precursor conditions to material failure (e.g. fatigue, wear, radiation damage), to explosions or fire (e.g. fuel leaks), etc. Repair may consist of self-repair (autonomic or system-directed), repair by the crew, or repair in a port or maintenance facility.

Temporary responses include:

- Redundancy by system or component duplication. This may be appropriate when the time available for a response is short and the cost of duplication is not too high: electronic systems can be duplicated reasonably inexpensively (in terms of weight, volume and cost), but duplication of a wing is less practical.
- Redundancy by over-engineering, for example by building excess strength into a structural component, or excess capacity into a power supply. This response is appropriate when the time available for a response is insufficient for repair, and the cost of over-engineering is less than that for duplication.
- Temporary repair that may be autonomic (e.g. autonomic repair of cracks in composite materials, or autonomic sealing of small holes in a pressure vessel of fuel tank with an embedded encapsulated foam) if the time available is short, or carried out by the crew. This is an appropriate strategy if its cost is less than that of redundancy.
- Isolation of a damaged component or section of structure, e.g. seal off a damaged section of a pressure vessel. This is similar to redundancy, but not identical. It is

possible only when there are components or sections that can be temporarily regarded as redundant and sacrificed, at least to gain time for a more effective response.

A significant component of the cost of most of these non-ideal responses, and of repair, will be additional weight in the vehicle. Vehicle weight is a prime concern to manufacturers and operators of aircraft, and it will determine fuel consumption in space applications. Nevertheless, current aircraft contain multiple levels of redundancy in electronic and hydraulic control systems, and significant over-engineering in primary structures.

The nature of the response to a threat or an event depends on the time available for a response to be made, and the time required for the various responses. The time available can be anything from milliseconds (or even less) to days or weeks. For very short times, the response must be effectively reflex, i.e. it must occur automatically with very little (if any) interaction with the rest of the vehicle: it must be a local response. Rapid, local responses are more likely to be temporary responses.

On the other hand, if a relatively long time is available for a response, there is time for reasoning and intelligence to be applied (if necessary), and something closer to an ideal response undertaken. Similarly, if a rapid response has produced a temporary solution, a slower more permanent response can be subsequently carried out. This is closely analogous, at least in principle, to mechanisms of wound repair in biological systems (Section 3), where multi-stage responses are normal. However, the first stages of mammalian wound repair mechanisms are slower and more complicated than would be required for, say, immediate repair of a ruptured pressure vessel in a space vehicle. The section on Materials and Structures (Section 4) also contains some comments on self-repairing materials.

5.6 Methodology for prioritization of measurands and sensors

The first task required for making a prioritized list is to determine the criteria by which priorities will be assigned. An important point in this regard is that priorities can only be set within a defined context. In this case, priorities will be set in the context of present day materials and capabilities: there appears to be no sensible alternative. However, this means that priorities will change as materials and structures with new capabilities are developed. The general procedure followed, though by a somewhat circuitous path, was as follows.

1. *Define the type of vehicle, and the nature of the missions it is expected to undertake.* It was decided to restrict consideration to the following specific types of vehicle. These are the same combination of vehicle and mission defined in Section 1 as A-D.
   - A space vehicle, which operates only in space and does not have to contend with atmospheric effects (vehicle A). It is assumed to operate from a space station, and must be capable of very long trips (e.g. years, decades).

Consideration was given to both crewed and un-crewed (and containing no biological material) versions of this vehicle.

- A vehicle in permanent Earth orbit, such as a space station (vehicle B). It is assumed that it must be manœuvrable, it must support a crew and passengers, and that it will provide docking for other vehicles (space vehicles, shuttles).
- A shuttle-type vehicle that operates between the Earth and near-Earth space destinations, such as a space station (vehicle C). It must be capable of operation in the atmosphere and in space, and carry passengers and crew. Trips will generally be short (up to a few days), landing and taking off from the Earth and docking in space.
- An aircraft, which operates entirely in the lower levels of the atmosphere (troposphere, stratosphere), carries passengers and crew, and lands and takes off from Earth (vehicle D).

These vehicle types and their functional sub-systems are listed in Appendix A5.3.

2. *Determine the threats to which such a vehicle might be subject.* In some cases, threats considered are actually consequences of other events; for example, explosions were considered as threats even though an explosion may be the consequence of a severe impact, a fuel leak, a nuclear malfunction, etc. Such events were nevertheless considered as distinct threats because of their characteristic consequences. Threats to individual functional sub-systems were considered in order to aid the analysis. The threats and consequences for an un-crewed space vehicle are listed in Appendix A5.4. Note that the threats listed are quite generic: there was no intention at this stage to consider the details of specific threats.

3. *Consider the worst-case consequence for each threat* to the functionality of the relevant subsystem, and make an assessment of the following factors, which are also listed in Appendix A5.4 (for an un-crewed space vehicle).
   - *The seriousness of the worst-case consequence* to the ability of the vehicle to complete its mission. This is assigned a numerical value in the range 1 to 5, where 5 represents a consequence that is fatal to the mission. Note that the assignments are skewed towards higher numbers because worst-case consequences are considered. There could, of course, be many less serious consequences.
   - *The time available following detection of a threat* or the occurrence of the immediate consequence, for a response to be made. This is categorized on an approximately logarithmic scale, from immediate (milliseconds or less), to seconds, minutes, hours, days, etc.
   - *The nature of the response*, which may be a permanent (ideal) response, or a temporary response that is essentially a means of increasing the time available to achieve an ideal response.

   An important quantity that has not been included in this list is the *probability of occurrence* of the threat. In evaluating priorities for sensors, this would normally be one of the most significant quantities to consider. However it has not been taken into account here for two reasons: firstly if a structure is to be ageless every possible threat will occur at some time (though this is probably something of a cop-out), and, secondly, we didn't have access to sufficient information to make even approximate relative judgements of these quantities.

4. *Determine the measurements that should be made*, and the quantities (measurands) required, to detect the threat and/or its consequence, both initially and subsequently. The primary and secondary measurements required for an un-crewed space vehicle are listed in Appendix A5.4. Appendix A5.5 contains a distillation of the information on the second page, listing the most serious threats and the measurands required to detect them and their consequences.

5. *List the types of sensors required to make these measurements*, and the vehicle sub-system in which the measurement has to be made. This is shown, for an un-crewed space vehicle, in Appendix A5.6.

The tables in Appendices A5.4-A5.6 are "work in progress", and it should be emphasized that the results reported are for generic, rather than specific, threats and measurements. So far, detailed consideration has been given only to the un-crewed space vehicle. Further work is needed to consider the other vehicle types in order to include the threats posed to and by people (crew and passengers), by the presence of the atmosphere, and by gravity. Nevertheless, the results for the un-crewed space vehicle represent an important sub-set of the requirements for an ageless vehicle. At least for the foreseeable future, it is the type of vehicle with the greatest need for agelessness: its missions may last for decades; it may travel enormous distances from Earth; it is the vehicle most likely to encounter unknown or unpredictable threats; and it will probably never be close to a maintenance base.

5.7 Results of prioritization exercise

The results of the prioritization exercise for an un-crewed space vehicle are contained in the tables of most serious threats (Appendix A5.5) and most important sensors and measurands (Appendix A5.6). But what do these results mean, and how useful are they?

It was recognized at the outset that the task of determining priorities for sensors needs some clarification. Firstly, as mentioned above, it depends on the properties of the materials and structures, the types of engines or sources of propulsion, sources of power for functions such as control, navigation, sensing, and many other factors. The Sensors Working Group decided it had little choice but to assume the vehicle would be built using current technology. However this raised contradictions: nobody would attempt to build an ageless vehicle using current materials, propulsion and electronics technologies. For example, self-repair mechanisms do not exist.

Just as importantly, current sensing, data processing and intelligent systems technologies are inadequate for the task. The Worksheets in Appendix A5 provide "in principle" rather than currently practical solutions to sensing and information extraction requirements. The priorities for sensors are therefore priorities for research in sensing systems rather than priorities for the deployment of sensors.

Another limitation was the lack of probability of occurrence information for many threats; in any case, at least for internal threats, this will depend largely on the materials and structures used and on manufacturing methods and practices. Many failures are due to inadequate fabrication techniques, or poor workmanship and/or inspection rather than inherent material or structural problems. These in turn may be caused by design faults, a lack of knowledge or understanding of the threats, or the constraints of cost.

These considerations meant that assigning strict priorities to various sensor types did not appear to be a very useful exercise. Instead, Appendix A5.6 lists a number of important sensor types, the measurands for which they could be employed, and the vehicle components where they might be required. All of these sensors would be required for an integrated health monitoring system for an un-crewed space vehicle. Research and development requirements for some of them are listed below. Emphasis is placed on avoidance of potentially catastrophic threats by detection of precursor conditions.

While the conclusions from this exercise may appear disappointing, a substantial benefit it provided was the impetus to investigate in some depth the threats and sensing requirements for the various aerospace environments.

i) *<u>Strain (acoustic emission) sensors</u>*
Measurement of strain, either on a material surface or an internal interface, at frequencies from dc to MHz, has the potential to enable detection of a variety of events or conditions, including impacts, fracture, cracking, debonding, pressure leaks, etc., that generate elastic waves. Such sensors could also be used as detectors for active elastic wave (ultrasonic) methods of damage evaluation. They are inherently suitable for use as embedded sensors in continuous monitoring applications. A number of suitable technologies are available, including piezoelectric "patches", thin-film resistive strain gauges, nano-particle films, optical fibre Bragg gratings, etc. These sensors are potentially among the most useful and versatile sensor types that could be deployed on an ageless vehicle, but realizing this potential represents a significant challenge for data processing.

ii) *<u>Techniques for detecting and evaluating material degradation in a range of materials and environments</u>*
Material degradation includes fatigue (thermal and mechanical), wear, erosion, embrittlement, radiation damage, corrosion, diffusion and a number of other conditions in which material properties are gradually degraded over a period of time. In some cases degradation could occur as a result of a number of detectable individual events (e.g. small impacts, microstructural changes), but in others detection of individual events would be impractical. All materials, including metals, polymers, ceramics, fibres and composites, are subject to various forms of degradation. The development of techniques for the early detection of the various

forms of degradation in the wide range of materials and conditions present in a vehicle is a major challenge. There is a great deal of current work directed at issues such as wiring insulation, adhesion, fatigue, and others.

iii) <u>*Self-testing diagnostics for control, navigation, communications, power systems*</u>
Any vehicle is at least as vulnerable to electrical and electronic failure as to mechanical problems. Space vehicles and modern passenger aircraft have multiple levels of redundancy in these areas to counter failures due to material degradation (e.g. thermal effects, radiation damage), software errors, information loss, etc. Improved system reliability and reduction in dependence on redundancy are research goals.

iv) <u>*Self-testing and calibration for the sensor network*</u>
This issue was discussed in subsection 5.2 above. Long-term reliability is a major issue for the deployment of embedded sensors in aerospace vehicles.

v) <u>*Continuous selective chemical sensors to operate in liquids and gases*</u>
Detection of contaminants in fuels, atmosphere, food, water, etc. and of leaks that might result in combustible or explosive conditions, require the development of chemically selective sensors suitable for continuous monitoring. For a space vehicle containing crew and/or passengers, which might contain a complete self-sustainable biosystem, a range of selective biosensors would also be required.

5.8 Current work on embedded sensors

There are a number of research and development programs underway directed at exploring the use of embedded sensors and actuators for structural health monitoring as well as for the development of adaptive structures. Here, we will briefly describe a few examples of embedded sensor activities.

- *The German ADAPTRONICS Project.*
  www.lp-adaptronik.de
  This is a €25M German Government funded project running from 1998-2002. It aims to develop adaptive structures based on the integration of piezoelectric fibres and patches into lightweight structures for active vibration and noise reduction, shape control, and micro-positioning. The project target is the implementation of this technology in the automotive industry, railway transport, mechanical engineering, medical applications, and aerospace technology. Many large and small German industrial companies (including Volkswagen, Siemens, etc.) are partners. They are involved with development of materials (PZT sol-gel fibres of 15 μm diameter, piezoelectric patches), composite technology (integration of the fibres and patches into materials and structures) and system development.

- *The Japanese Smart Material and Structure System Project.*
  This program, funded by MITI/NEDO, has groups working in health monitoring, active adaptive structures, smart manufacturing, actuator materials and devices, and other areas. It has just completed 4 years of a 5 year program and is in the final stages of developing two major demonstrators: one for damage detection and suppression, and one in noise and vibration suppression. The first of these involves real-time damage (impact) detection using acoustic emission as well as embedded optical fibre sensors, whole-field strain mapping, damage suppression using embedded shape memory alloy films, and other components. The second demonstrator is aimed at the active vibration cancellation and acoustic noise suppression, primarily using piezoelectric actuators. These demonstrators are quite substantial (1/3 scale of a section of B737-class aircraft fuselage), with different carbon fibre reinforced polymer panels containing different sensors.

- There are a number of activities aimed at using embedded piezoceramic elements as displacement sensors and actuators, mainly for NDE purposes. The elements may be used in actuator mode to excite a structure and/or in sensor mode to register the vibration response. For arrays of such elements, signal processing is then employed to interpret the results with respect to the locations and types of deformations and to interpret them in terms of impacts, damages etc. Some recent work, by a US group concerned with real-time impact and damage monitoring, has been reported by Martin et al. (2002) and Ghoshal et al. (2002). An example of a commercial implementation of embedded piezoelectric element arrays is the SMART Layer® made by Acellent (http://www.acellent.com/).

- Optical fibres have emerged as very sensitive and versatile deformation sensors. The ability to integrate a large number of individual sensors on a single fibre allows the mapping of the distribution of deformations along the length of the fibre with high spatial resolution. Numerous publications describe activities related to the use of embedded fibre optical sensors for structural health monitoring in transportation, civil engineering, and a variety of other applications. Examples can be found in the relevant literature, e.g. a recent monograph (Othonos and Kalli, 1999), a review of sensing methods (Alasaarela et al., 2002), the proceedings of the IEEE International Conferences on Optical Fibre Sensors, etc.

- Some other groups and areas of interest include:
  - Innovative Dynamics Inc. (http://www.idiny.com/abstracts/wtfsgevm.html). Wireless thin-film strain gauges for embedded vibration measurement.
  - The University of Texas at Austin, Microelectromagnetic Devices Group (http://weewave.mer.utexas.edu/MED_files/MED_research/mems_sum.html). Miniature IC inductive proximity sensor. Potential applications using two-coil planar inductive devices include bearing wear sensors, small gap measurement, and accelerometers. Micro-machined Fabry-Perot chemical sensors.

– University of Minnesota, (http://www.me.umn.edu/divisions/design/composites/Projects/Embedded Senor/Embedded Sensors.html). Two Microelectromechanical systems (MEMS)-based piezoresistive (n-polysilicon) strain sensors on a thin Si_3N_4/SiO_2 membrane with improved sensitivity were successfully designed, fabricated and calibrated.

5.9 Sensors for the concept demonstrator

The Sensors Working Group discussed sensing options for the concept demonstrator whose development is to be started in the next phase of the project. It was decided, on the basis of the considerations outlined in this section, to suggest that the main initial task of the demonstrator should be impact detection. The deployment of strain sensors on the surface of an enclosed vessel would have the following advantages:

- Commercial sensors are available, but there are opportunities as the project progresses to develop and trial new sensor technologies, such as the CTIP nano-particle strain sensor, thin-film MEMS sensors or piezoelectrics.
- Detection of impacts of a wide range of energies is a problem of concern to NASA.
- There is scope for expanding the use of the sensor network to investigate other problems at a later stage.
- It is expected that some progress could be made using relatively straightforward data processing algorithms in the first instance, with the opportunity for a substantial research effort to improve the performance of the data processing as the project progresses.
- Other sensors, such as temperature and pressure sensors, should also be deployed to provide complementary information regarding external conditions, puncturing of the pressure vessel, etc. Such sensors may also be necessary for calibration and the correct interpretation of the strain sensors.

Further details of this proposal will be described in Section 9 of this report.

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6. Intelligence Issues for Ageless Vehicles

6.1 Introduction

The objective of this project is to develop and discuss the concepts required for an intelligent integrated health monitoring system for potentially ageless aerospace vehicles. This section discusses the issues involved in achieving intelligence in such a system. But what do we mean by "intelligence"? Which aspects of the system require intelligence? How should the intelligence be structured? How will we know if the system is sufficiently intelligent?

There appears to be no simple or straightforward definition of intelligence, despite the efforts of countless philosophers and scientists. It is equally difficult to define precisely what is meant by related terms such as "thinking", "meaning" and "consciousness". Yet these are terms that are used every day, and we all have a reasonable idea of what we mean by them. In general, operational definitions are used: while it is difficult to pinpoint the borderline between intelligent and unintelligent behaviour, we like to think we will recognise intelligent behaviour when we see it. But is the collective behaviour of a flock of birds intelligent? Insofar as it can be modelled by a small number of simple rules of interaction between individuals, we would probably lean to the negative. But what about ant colonies? Although individual ants appear to be unintelligent, and to interact with each other via a small number of simple messages, the colony as a whole appears to display intelligent behaviour that evolves in response to environmental changes. Another issue, touched on in the next subsection, is that our working definition of an intelligent process or system may change according our understanding of it.

Hofstadter (1980) listed the following abilities as essential for intelligent behaviour.

- To respond to situations very flexibly.
- To take advantage of fortuitous circumstances.
- To make sense out of ambiguous or contradictory messages.
- To recognise the relative importance of different elements of a situation.
- To find similarities between situations despite differences that may separate them.
- To draw distinctions between situations despite similarities that may link them.
- To synthesize new concepts by taking old concepts and putting them together in new ways.
- To come up with ideas that are novel.

This is a formidable list of requirements, but it is certainly possible to identify a number of these abilities that would be needed to ensure the survivability of a vehicle in situations that may be complex or unpredictable. How well each of these behaviours need to be developed, of course, is another matter.

Why do we need intelligence in an ageless vehicle? Firstly the sensing system will be extremely large and complex. With the development of MEMS and nanotechnology, a vehicle may contain tens of thousands to millions of sensors, each providing continuous streams of data. Some sensors will malfunction, some will be out of calibration and some will lose data due to faulty communication paths. This is inevitable. More importantly, the vehicle will be subject to not only various combinations of known threats, but at some times of its life it will encounter threats that are not currently known. The processing of this vast amount of complex data to produce information, and ultimately a representation of the state of the vehicle will require a number of the abilities listed by Hofstadter. The system will need to learn how to process data in a changing environment in which damage and malfunction of the sensing system may be as significant as damage to the underlying structure.

The monitoring system will also be required to draw conclusions from the information deduced from the sensed data, and to make intelligent decisions on courses of action to repair damage and to proactively mitigate further damage. Again, this will require a number of the abilities identified by Hofstadter.

The next subsection discusses intelligence and where it is needed then, in turn, means of achieving intelligence, the role of learning and adaptability in the demonstration and attainment of intelligence, the complex topics of representation and conceptualization, and, finally, proposed subjects on which future research should be concentrated.

These discussions are generally based around the use of a multi-agent intelligent system. Based on observations of the vulnerability of centralized biological systems (Section 3) and the collective wisdom of the artificial intelligence community, there seems little doubt that such a structure is preferred. Systems of autonomous agents are discussed in subsection 6.3. Whether there should be a hierarchical structure amongst the agents, and how to structure and achieve a suitable hierarchy are complex questions that are discussed here and will be the subject of future research.

6.2 Where intelligence is needed

A scenario

It is extremely hard to argue about the precise nature of artificial intelligence in any project. If an algorithm is well understood, then it immediately becomes "dumb" – a good example is feedback, well-known in engineering: not many people would call it now an intelligent adaptive algorithm, while 50 years ago Norbert Wiener argued that feedback is at the core of learning cybernetic machines. On the other hand, if a concept is not transparently reducible to simple algorithms, then it is a kind of magic by which we seem to get something from nothing – a good example is emergent behaviour, when it is unclear from where the benefit is coming.

We would like to resolve this paradox in the context of the model system introduced in Section 2. The system will be made of units that we refer to as "tiles." These tiles will not only form a physical shell for an aerospace vehicle, but will also have sensors, logic, and communications. The tiles may be mobile, carrying their physical and logical capabilities to wherever they are needed and performing active measurements using inbuilt sensors. There may also be mobile agents that forage for potential problems. What we will say about multi-agent systems applies very well to these situations. In terms of intelligence, the requirements of the tiles will vary greatly, as expressed in Figure 6.1. Single tiles may need to make fast and automatic responses to sudden damage, while collections of tiles, or perhaps some individual tiles, may develop more intelligence as required. All points on this scale from reactive behaviour to cognitive behaviour will be equally important to the survival of the vehicle.

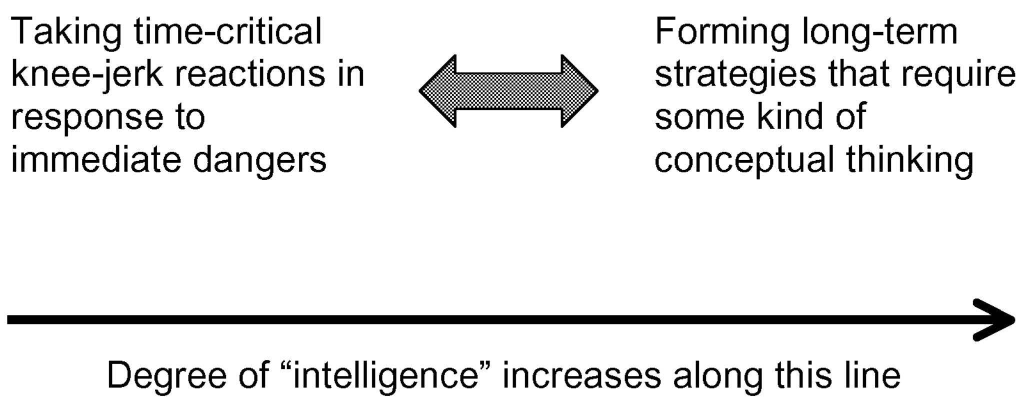

Figure 6.1: There are many responses that an ageless vehicle will have to make, and different kinds of intelligence are required. Without offering a specific definition of intelligence, we suggest that the kind needed for sentience increases as shown. All kinds, however, are necessary for the vehicle’s survival.

The model system will have an ability to develop a representation of the state of damage of the structure – we might call this a perception of its state. It will also have an ability to decide on a coordinated and adaptive strategy for dealing with the damage – for example, coordination of sensors, prioritization of repair, and mitigation of further damage using various means.

After a sensation of damage – we have chosen this phrase carefully – such a strategy might lead to the following sequence of responses:

1. Tiles re-configure their connections by seeking or activating new communication links, and disabling or downgrading some old links.
2. Tiles self-organize into new “supertiles” with some collective metrics obtained from their sensors.
3. Appropriate short-term repairs are made with an appropriate urgency.
4. As time passes tiles monitor repairs and run a series of self-tests confirming the new coordination ability.
5. Tiles cooperate, or refer to a source of higher intelligence, to develop a long-term strategy for replacement of damaged parts, if necessary, and avoidance of similar damage in the future.

While developing our system we will look for emergent behaviour in preference to pre-programmed behaviour, because the former is likely to be more robust in uncertain environments.

In the remainder of this section, the reader may understand "agents" to mean tiles of the model system. As the project matures and develops, other incarnations will appear.

6.3 Integration of perception, reasoning and action

For a vehicle to carry out useful physical tasks in complex, unstructured and response-time varying environments it has to continuously transform raw sensory **data** into **information** (interpretations) and then into context-sensitive **knowledge** (concepts). This requires:

- flexible sensor instrumentation, adequate for comprehensive acquisition and efficient pre-processing of signal data (enabling robust fusing of data-sets provided by multiple sources, extraction of meaningful context-sensitive interpretations, continuous maximization of accuracy and reliability of the interpretations, etc.),
- an adaptive control system with sufficient computational and algorithmic support, capable of selecting diverse modes of operation (centralized/distributed control, hierarchical/horizontal organization, programmable/emergent behaviour, etc.),
- an action (navigation) system combining reliable collision-free navigation behaviours (varying from reactive short-range obstacle avoidance to high-level long-range path planning algorithms), efficient observation and/or warning tactics (i.e., advance warning probes), etc.

The main research challenge in this area is to seamlessly integrate the three major components (perception, reasoning and action) in an efficient and reliable architecture.

Inspiration from nature

We only know about intelligence through our experience of it in the natural world – a world that includes ourselves. A wide range of natural phenomena relevant to our study of ageless vehicles is discussed in Section 3. A few examples are sufficient to show that useful intelligent behaviour may arise in very different ways. They range in intelligence but are all aimed at survival of the individual or the group. The topics mentioned here, such as agent-based systems and learning systems, are addressed later in this section.

Ants

Colonies of ants exhibit complex emergent behaviours, including building nests and collaborating to gather food, both of which require sophisticated coordination. Evidence is gathering, however, that a relatively simple set of rules for ants' individual behaviour is responsible for effective foraging, colonization and warfare, all on a massive scale. High-level collective behaviours can be synthesized from simple interactions like pheromone marking (Calderoni and Marcenac, 1998). New approaches to programming (Shouse, 2002) will be essential for guiding useful emergent behaviours for an ageless vehicle. Johnson (2001) discusses emergence from a popular perspective.

An ant colony is a good example for discussing emergent intelligence. When we understand a single ant we may say that it is not intelligent, but the ant colony viewed as a single entity may be viewed as intelligent. However, when we understand the emergent behaviour due to ant interactions, we may say that the colony is no longer intelligent, but predictable! The paradox of artificial intelligence thus appears in natural systems also.

Bees

Similarly, bees build hives and gather nectar, and their elaborate communication techniques using "dance" have been observed by generations of naturalists. Bee foraging, a rich field for behavioural studies, is beginning to be understood at a neuronal level (Douglas, 1995; Montague et al., 1995). In the words of Menzel (2001):

> "The wealth of complex forms of learning in the context of foraging indicates basic cognitive capabilities based on rule extraction and context-dependent learning. It is believed that bees might be a useful model for studying cognitive faculties at a middle level of complexity."

The relevance of such studies to our problem of ageless vehicles is that we might hope to reproduce such a level of complexity, whereas modelling human capabilities is no doubt many years away. The aim is to create a system that can deal with real-world uncertainty:

> "The analysis of risk-sensitive foraging is beginning to explore the psychological and cognitive mechanisms involved in decision-making under uncertainty as well as the more traditional functional analysis." (Real, 1996)

Birds

A classic example of emergent, rather than hard-coded, behaviour is the **flocking** behaviour of birds. It can be simulated with three simple rules: (i) maintain a minimum distance from other birds or other objects; (ii) match the velocity of birds in the neighbourhood; (iii) move towards the perceived centre of mass of the nearby birds (Levi, 1997). Faced with an obstacle, the simulated flock splits around and reunites beyond it.

Kangaroos

A mob of kangaroos behaves as an agent-based system with coordination dependent on environmental factors. Typically there are 20 kangaroos altogether, split into groups of 2-3 for foraging. In times of danger, however, the entire mob will gather and collaborate. Similarly, in an ageless vehicle we hope that agents responsible for maintenance and repair would combine their resources to deal with major problems.

Whales

Killer whales have developed hunting strategies that demand advanced reasoning capabilities, a concept of acting for the benefit of the group, and an ability to pass on knowledge by teaching the young (Joordens, 1997). The role of learning in an ageless vehicle may be two-fold: firstly, not all survival scenarios can be anticipated by human designers so a vehicle should learn from experience; secondly, learning is an essential ingredient of sentience.

6.4 Achieving intelligence

How do we achieve intelligent behaviour? Many different kinds of response are required of our ageless vehicle, some simple and automatic, some requiring long-term memory and conceptual ability. Therefore we can consider several routes to an intelligent system, and our vehicle might make use of more than one.

Rule-based systems

Computer programs display rule-based intelligence. So do "expert systems" representative of early types of artificial intelligence. If we know what the right action is in a given situation, why make our ageless vehicle figure it out or learn it? We may as well code it in. The speed of this approach is likely to help our vehicle out of sticky situations.

The problem is, such systems are known to be "brittle" because they can fail dramatically in situations that were not anticipated. The performance of rule-based systems is limited by our own ability to conceive all possible situations, and our ability to write robust software. Being human, we probably fall short of what is required in both respects.

Declarative logic programming and deductive databases use "inference/derivation rules" for defining derived concepts and heuristics (without any state-changing effects). Rule-based systems of this type can be either goal driven, using backward chaining to test whether some hypothesis is true, or data driven, using forward chaining to draw new conclusions from existing data. In either case, this approach relies on some kind of an inference engine (a theorem prover), often resulting in computational inefficiency.

On the other hand, "event-condition-action rules" specify only the reactive behaviour of a system in response to trigger events (assuming that all the possible situations can be anticipated). The use of a rule-based system implementing a reactive strategy has been proposed in, for instance, programming NASA's Mars rover (Harmon, 1989). Typically, no matter how complex a rule-based system is, it is always a reactive one with no predictive capability. Therefore, it cannot adapt as its environment changes.

In addition, there are various programming languages and systems based on the rule concept in general, but without any precise semantics for rules.

Systems of agents

The architecture of an ageless vehicle is likely to include very diverse components: simple, expendable, and continuously producible advance-warning probes, mobile and topologically compatible solar panel tiles without a single point-of-failure, high-precision navigation and targeting modules, controllers with adjustable autonomy and adjustable communication policies, and so on. These components should interact with each other and **propagate control** within the vehicle.

It is conceivable, for instance, that groups (swarms) of distributed physical entities (sensors, controllers, actuators) may be more efficient and more robust under certain circumstances than a centrally controlled vehicle. The main research challenge in this area is, therefore, designing and developing an adaptive control system capable of evolving under, and adjusting itself to, different circumstances.

Swarms of physical entities cooperatively solving tasks, which no one of them could complete alone, form multi-agent systems. These systems are a special class of complex systems, typically characterized by the following factors:

- a number of agents, none of which has complete capabilities to solve a problem;
- absence of global system control;
- no single point-of-failure;
- data is decentralized;
- multi-platform functionality (some agents run on low-end platforms, some on high-end platforms);
- computation is asynchronous.

These properties are apparent in our model system introduced in Section 2.

A hierarchy can be induced: what if our agents are themselves composed of agents? Figure 6.2 shows one way to visualize an intelligent system with diverse agents. It is possible to regard the brain as an agent-based system. Not only do neurons communicate in unimaginably complex ways (each of the 10^{11} neurons in the human brain connects with about 10,000 others) but neurons themselves are not simple at all and are perhaps worthy to be regarded as agents. Koch (1997) writes:

> "Neurons and their networks underlie our perceptions, actions and memories. The latest work on information processing and storage at the single-cell level reveals previously unimagined complexity and dynamism."

Also, from Fellous and Linster (1998):

> "Finally, we present a detailed mathematical overview of how neuromodulation has been implemented at the single cell and network levels in modelling studies. Overall, neuromodulation is found to increase and control computational complexity."

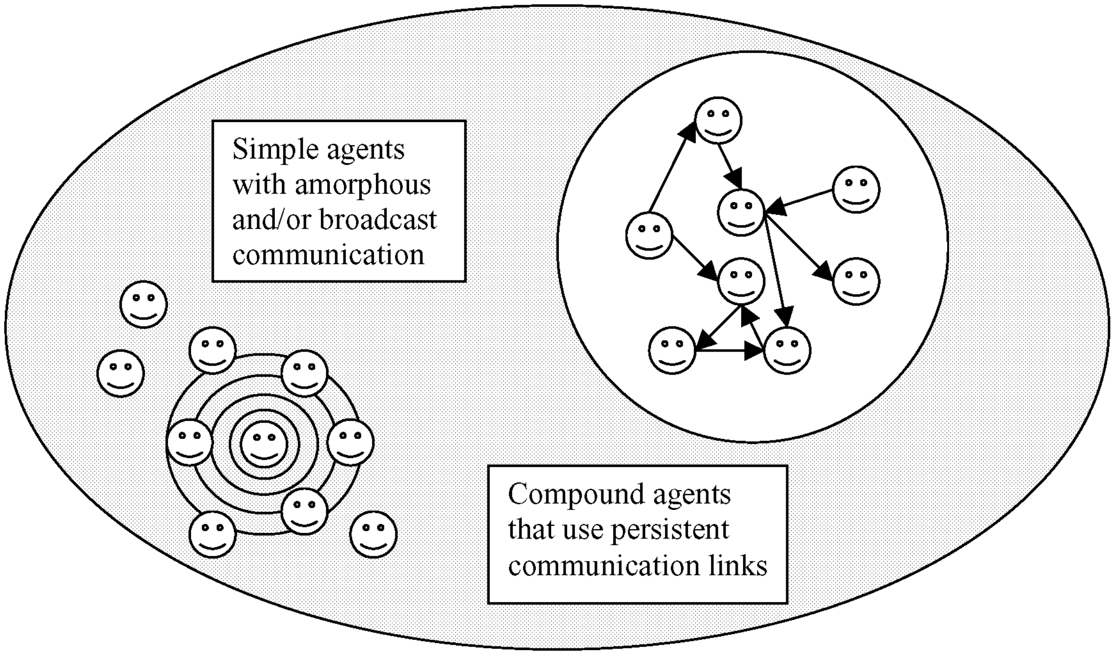

Figure 6.2: A range of intelligent agents may coexist to build the intelligence required for an ageless vehicle. The complexity of their interactions is governed by the media available for communication. Here, a group of agents using broadcast communication, with a connectivity that depends on proximity, is contrasted with a group of agents tied into a network of defined links, which itself may be considered an agent. On the one hand, having persistent links reduces flexibility; on the other hand, the information content of the link structure adds to the compound agent's intelligence.

Control of emergent behaviour

More often than not, multi-agent systems show "emergent behaviour", which is not explicitly programmed. Several algorithms for spatial self-organization exemplifying the use of emergent behaviour are given by Ünsal and Bay (1994, 2002): self-organizing agents can arrange themselves geometrically in two- and three-dimensional space using only local information, obtained by its own sensors. A quite sophisticated multi-layered hierarchical motion planning strategy for a class of self-reconfigurable modular robotic systems is described by Prevas et al. (2002). Emergent behaviour in colonies of ants and bees is mentioned above.

It is possible that emergent behaviour leads to intelligence as we experience it in the natural world. This is a new field of research with a great deal of work yet to be done, but we can suppose that the complexity of emergent behaviour increases with

- the sophistication of the agents,
- the variety of the agents, achieved either by original design or by a learning process that is unique to each agent's experience, and
- the complexity of the communication connections between agents.

This is essentially an information-theoretic argument, in that more variety of agents and connections allows a greater number of states to be achieved. A plausible tabulation of degrees of intelligence against agent and connection complexity is shown in Table 6.1. Whether or not this is correct, it is certainly a useful basis for embarking on research in this area.

In general, tasks could be managed more easily and reliably if emergent behaviour is engineered by programming (situated) agents locally – without reference to the knowledge of the global task structure. Moreover, in this case, failure or partial malfunction of agents would not critically endanger the vehicle. Thus, programming and maintaining relatively simple distributed agents reduces the complexity of control, which would otherwise have to be globally imposed on all components.

The main question that has to be solved, however, is how to **constrain** the emergent behaviour, or, in other words, how to produce and retain desirable emergent behaviour while avoiding potentially damaging patterns of agents' interaction. Current research shows that the problem of systematically transforming the global task to individual behaviour models (top-down approach) is yet to be resolved. A solution to this problem would provide a much-needed breakthrough.

Degrees of intelligence of a network of agents		AGENTS		
		Simple / Similar	In-Between	Interesting / Diverse
CONNEC-TIONS	Random / Amorphous	*Low*	*Medium*	*High*
	In-Between	*Medium*	*High*	*Higher*
	Intentional / Architectural	*High*	*Higher (Brains?)*	*Highest*

Table 6.1: A possible classification of emergent intelligence, using an information-theoretic perspective that assumes that more structure means more intelligence. A third dimension, not shown, is the range of connections – for example, the number of agents reached by a broadcast communication. Alternatively, this dimension can be viewed as the persistence of connections. A broadcast communication would reach a subset of all agents, and these connections would persist while the agents, if mobile, remained within range. Adding a coding scheme would permit agents to set up persistent connections, continued or broken by agreement, creating a structure that could represent information or perform processing.

If all agents are the same, the variety of behaviours of the group must be bounded in some way. If there are a finite number of different agents, the same applies. An analogy might be found between agent systems and chaotic systems. Chaos theory might be applied to determine bounds of behaviour, and to discover how to ensure that the system remains in a state that is useful. Perhaps intelligence arises from a chaotic state?

Coordination in multi-agent systems

Agents are expected to be engaged in complex and frequent **patterns of communication** with each other. An inter-agent communication structure (protocols, schedules, agreements, patterns, etc.) is directly related to the coordination within the multi-agent system. Current approaches to activity coordination in multi-agent systems range from strictly top down (plan-based coordination) to purely emergent (reactive coordination), with many hybrid variants, each having its specific advantages and disadvantages.

One promising approach enabling a rigorous comparative analysis of various hybrid methods and forms of multi-agent coordination would be to use the relative **information entropy** as a precise measure of the amount of freedom of choice (the degree of randomness) contained in the agents' joint beliefs (Prokopenko and Wang, 2002). Intuitively, the system with near-zero entropy (almost no "misunderstanding" in joint beliefs) has a higher coordination potential than the system with near-maximal entropy (joint beliefs are almost random). It has been recently pointed out in the literature (Suzudo, 2000) that the entropy trajectory (as a temporal pattern) is a useful descriptor for a variety of self-organized patterns (and potentially intelligence). For example, certain types of cellular automata have simple entropy trajectory and do not renew their self-organized pattern, converging quickly to either very low or very high values (i.e., have a fixed-point entropy trajectory). Others have an irregular entropy trajectory and renew the self-organized pattern.

The main challenge is to investigate information-theoretic complexity of various communication policies, and relate it to agents' coordination.

In general, the process of self-organization (e.g., self-reconfiguration) is not random but needs information transfer to be successful. For instance, the peripheral nervous system is capable of regenerating neurons by re-growing severed axons within a myelin sheath (made by Schwann cells). When an axon is severed, it activates multiple signalling links by secreting mitogens that stimulate Schwann cells to divide[5]. As a result, Schwann cells divide to form a pathway along which the axon grows.

Another example of self-organization requiring some underlying information is the process by which a protein chain of amino acids folds into a particular 3-dimensional polymer configuration. The final thermodynamically stable structure is typically obtained in a few seconds, despite a huge number of all possible configurations. One possible explanation of this phenomenon for 3x3x3 27-mers (Sali et al., 1994) involves an energy function expressing the total energy present in the interactions between the elements of the protein chain. The fast-folding sequences can be characterized by a wide gap of energy between the folded structure of least energy (the native state) and the next best (least energetic) one. This gap is not observed in slow-folding chains. In other

[5] Mitogens belong to a group of related growth factors with diverse biological functions that are now known collectively as the neuregulins. Neuregulin, the neuron-derived molecule responsible, in particular, for Schwann cell proliferation, is very versatile – it is also involved in nerve-muscle communication, and in the aberrant growth of cancer cells (Vikhanski, 2001, p. 80).

words, only sequences with a pronounced minimum energy can be expected to fold into their minimum energy structures. Importantly, the total energy of a sequence is assumed to depend only on nearest neighbour contacts – in a sense, a spatial folding code (a set of rules) contained in the sequence "leads" a protein to fold to a unique native state. Moreover, a similar analysis of 5x5x5 125-mers (Dinner et al., 1996) has shown that a sequence has "cooperative" structures in its native state: contacts are "cooperative" if formation of any one contact increases the probability of formation of the others. In other words, the search is not random, but is significantly restricted by the fact that only a portion of the energy surface is accessible – that is, certain regions are too high in energy to be sampled with a significant probability by folding trajectories (Dobson et al., 1998).

In summary, it could be argued that global self-organization emerges as a result of interactions involving transfer of information that is embedded locally.

6.5 The role of learning and adaptability

Feedback

Very useful degrees of adaptability can be achieved through feedback. Brain-inspired architectures already capitalize on this:

> "Dr Harrison and his supervisor at Caltech and co-founder of the Telluride summer school, Christof Koch, identified the various processes taking place in the so-called lamina, medulla and lobular-plate cells in a fly's brain as being worth implementing in silicon. These cells form a system that allows the fly to detect motion throughout most of its visual field – letting the insect avoid obstacles and predators while compensating for its own motion."
>
> [...]
>
> "To prove that the chip not only worked, but could be useful, Mr Harrison attached it to a robot that had one of its wheels replaced by a larger-than-normal one, making it move in circles. When instructed to move in a straight line, feedback from the vision chip – as it computed the unexpected sideways motion of the scenery – was fed into the robot's drive mechanism, causing the larger wheel to compensate by turning more slowly. The result was a robot that could move in a straight line, thanks to a vision chip that consumed a mere five millionths of a watt of power." (*The Economist*, 20 September 2001; also Koch, 1997)

Feedback is a valuable tool because it is so well understood in many fields of engineering.

Learning

A unique entity is shaped by its experience. Learning may be the only way to achieve conceptual intelligence of any real depth – the complex and marvellous development of a child is the best model we have, and a child needs to interact with the world intensely for several years in order to grow up. Achieving intelligence through learning is attractive because it removes responsibility from the developer. A deterministic solution is perhaps not practicable due to the limits of our own conceptual abilities and on our ability to write robust software. Instead, a learning system requires us to set up a robust framework within which learning can take place.

We can conceive a system of agents that, as an entirety, is able to learn. We can also conceive a system of agents each of which is able to learn. Ruppin (2002) develops this idea as a tool for understanding biological nervous systems. In such a system of agents, each agent would be different, leading to true diversity of behaviour.

But how do we define rewards to guide behaviour? The behaviours we want don't have rewards that are simply measured like, for example, acquiring food (Schultz, 1998). Are there alternatives to a rewards system, perhaps involving "non-conscious biasing" proposed by Bechara et al. (1997)? The training regime that we apply to our learning system, and the methodologies for passing on the lessons learnt by one vehicle to another, would be crucial to the development of useful conceptual intelligence. We hope that our vehicle will not have catastrophic failure, but we would like it to learn from its mistakes, and from situations where it succeeded but could have done better.

And how do we implement a learning system? Neural networks, while mimicking the brain, have certainly not achieved animal-like intelligence. More recently, support vector machines (Cristianini and Shawe-Taylor, 2000) have a firmer theoretical basis. However, do they replace neural networks, or brain-inspired systems generally, or do they solve a different class of problems? Present-day neural networks are very far from exhausting the possibilities of a brain-inspired thinking architecture. There is much work yet to be done in this field, and many lessons to be taken from natural systems. Representation of information and knowledge is a key concern, which is discussed below.

Evolution

We should be careful to distinguish learning and adaptability from evolution. Evolution refers to the development of a population, not an individual, and we are not proposing at this stage to develop a fleet of evolving vehicles – this would require individual vehicles to be expendable so that the fleet could survive, a situation that is beyond the scope of the present project on ageless vehicles. We are suggesting that an individual vehicle can learn from its experiences, short of catastrophic failure, in different environments.

However, a vehicle may maintain a large community of tiles, and these could indeed be "drawn" from an evolutionary pool. There are precedents for artificial evolutionary systems. Evolvable software has been proposed for many years, and with practical results:

> "And so dawned the third age of AI. Its boosters abandoned hopes of designing the information-processing protocols of intelligence, and tried to evolve them instead. No one wrote the program which controls the walking of Aibo, a $1,500 robotic dog made by Sony, the Japanese consumer-electronics giant. Aibo's genetic algorithms were grown—evolved through many generations of ancestral code in a Sony laboratory." (*The Economist*, 20 December 2001)

An interesting biological parallel of evolutionary learning is an ant colony that, as an entity, can learn, or adapt its behaviour, on a timescale longer than the lives of the individual ants. Even though the life span of an individual ant might be less than a year, the behaviour of the colony will be modified on a 10-15 year time scale, as pointed out by Johnson (2001).

Evolvable hardware (EHW) is an IBM initiative:

> "Today, it is possible to contain the entire genetic algorithm – blueprint creation, fitness evaluation and reconfiguration – within a single microchip, and to run thousands of evolutionary trials in a fraction of a second. Although they were invented some 30 years ago, genetic algorithms have hitherto been run generally in software, where they placed a large and often prohibitive burden on the processor's time. EHW avoids this problem by running its genetic algorithms in hardware.
>
> "That is the crucial difference. In any digital device, wiring instructions into the actual hardware, rather than running them as part of the software, invariably boosts the speed of operation. In EHW, the speed advantage is so significant that the genetic algorithm for problems that could not have been solved in software can be cracked in real time – i.e., with the solutions being produced as fast as the problems are fed in. This speed and flexibility makes EHW ideal for handling situations that vary rapidly." (*The Economist*, 22 March 2001)

6.6 Representation and conceptualization

Where is the knowledge?

How are the data, information, and knowledge represented? Representations are intrinsic to discussions of behaviour and learning – for example, sensory representations and motor representations are assumed by Douglas (1995) – but is there a firm idea of what they are? So far, work on artificial intelligence seems to lean towards developing algorithms rather than framing the data they operate on, yet perhaps we cannot understand the required basic operations until we understand how the physical and conceptual world should be represented. For wide-ranging discussions on representation in the human mind, see Dennett (1991).

Data are related to memory, and there has been a lot of work on the mechanism of memory (Menzel, 2001). How close are we to knowing the "meaning" of synaptic connections? On the one hand, we need to understand how high-level concepts are represented in order to conceive operations on these concepts to generate responses. On the other hand, a lot of work on neural networks seems to be "blind" in that no interpretation of conceptual understanding is made about their operation. We trust the system to come to the right conclusion, making internal representations only it can understand. This may or may not be the right way to approach the problem.

In the literature concepts are seen as a means of making the problem-solving task tractable – for example, Müller (2000) writes that

> "… concepts play an important role in representing circumstances accessible through the sensors of a cognitive agent, and in accessing inner states necessary for an overall problem-solving by the cognitive agent. […] 'Cognitive' robots, most probably, will get at least part of their autonomy from the stable recognition of known situations with the help of concepts, and from the flexibility with which they can react on changing circumstances via modified or new concepts."

Stewart and Wood (2001) emphasize that concepts are high-level data that are refined with the passage of time:

> "Invariably, that part of learning modelled is acquisition: the process of acquiring 'new' concepts or knowledge, to the extent that concept acquisition and learning are often viewed as synonymous.
>
> "Here, we make the case that psychology provides us with a much richer view of learning, in which acquisition plays a key part, yet which is balanced by complementary processes which actively modify previous learning."

Reasoning about change

An important characteristic of autonomous agents (controlling their actions without direct intervention of humans) is their **temporal continuity** – agents are continuously running processes, rather than functions with fixed inputs and outputs. The dynamics of agents' beliefs is, therefore, an important issue related to the agents' abilities to modify their behaviour on the basis of new information, deal with unexpected changes in the environment, and recover from errors.

The agents' capability to maintain dynamic beliefs is based on another very important cognitive skill – the ability to remove itself from the current context. This ability is sometimes informally referred to as "possession of a reality simulator" (Joordens, 1999). Running a **reality simulator** allows the agent to reflect on past behaviour and project the outcome of future behaviour. There is a conjecture that higher mental states emerge as a result of a reality simulator: "an animal with no reality simulator basically lives in the present tense, and sees the world through only its eyes, at all times", while "the possession of a reality simulator may also allow an organism to experience many of the high-level cognitive processes that we identify with being human". Moreover, an agent with a reality simulator is more likely to engage in cooperative behaviour because of its ability to conceptualize rewards to others (the whole system), and long-term rewards to itself.

Thus, design of efficient and robust techniques enabling flexible reasoning about change (events, actions, etc.) would directly contribute to the vehicle's recognition of its state relative to its past and its future.

6.7 Proposed foci for intelligent systems research

To achieve the long-term goals of this project we suggest three areas of research in intelligent systems, matching well with this section's three major subsections on achieving intelligence, the role of learning and adaptability, and representation and conceptualization.

- Study coordination in multi-agent systems:
    - Information-theoretic analysis of multi-agent systems.
    - Self-organization and adaptive control of emergent behaviour.
    - Bounding emergent behaviour with reference to chaotic systems.
- Assess the role of learning:
    - Effectiveness of learning compared to deterministic systems.
    - Effectiveness of different learning techniques.
    - Methodologies for training and passing on acquired knowledge.
- Investigate the representation of data, information, and knowledge:
    - Representing the structure of knowledge in a distributed system.
    - Balancing redundancy and robustness of information.
    - Relationships between representations and algorithms.

In the shorter term, our research will be focused on the model system described at the beginning of this report, and will be grounded experimentally using the software simulation described in Section 8. The simulation is built on a SmartUnit object that has logic, sensing, communication, and other capabilities. It will be an effective test-bed for studying multi-agent systems, and with it we hope to demonstrate, for instance, that self-organizing tiles survive longer than hard-wired ones. Or that tiles that learn from their mistakes, and share the knowledge, detect damage earlier than tiles with fixed input and output. Or that a distributed and coordinated system of tiles conducts repairs in a more robust way than a centrally-controlled one. All of these and many other aspects will be investigated during the project, as we demonstrate intelligent behaviour of different kinds and increasing levels of sophistication.

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7. Intelligent Signal Processing and Communications

7.1 Introduction

Like the human body, an ageless vehicle must be thought of as a completely integrated system, with all aspects of sensing, internal communications, perception and decision-making, self-repair and action being strongly interdependent. To some extent the various components may be considered separately, as is commonly done in the case of the body in the differentiation of the many medical specialties, but a proper understanding can only be obtained from an integrated perspective. For a body to operate correctly (or at all), all the internal systems must work together: the human body is an incredibly complex integrated system.

This is equally true of an ageless engineering structure. The processing of sensed data, firstly to provide information relating to damage to a vehicle, secondly to enable the vehicle to form a perception or representation of its overall state, and ultimately to enable it to make decisions and initiate actions for repair or damage mitigation, cannot sensibly be considered independently of the number and mix of sensors, the materials in which they are embedded, the information required of them or the type and structure of the "intelligent system" (of which the data processing and communications are core components).

Similarly, the communication structure, media and protocols are part and parcel of the overall system design. Referring again to the human body, this point is reinforced by the fact that the main communication pathways of the central nervous system are cells (neurons) whose nuclei form an integral part of the brain[6] (Section 3). The structures of the data processing, intelligence and communications systems must be considered together. Questions relating to the processing of data locally (at a sensor or local module site), regionally (for a number of sensors or local modules) or globally depend on the sensors and the information required from them, on the communication capacity and on the structure of the intelligent system (the independent agents and their hierarchy).

For these reasons little distinct work was done on methods of data processing and communication system structures during this phase of the project, despite the central importance of the subjects. Communication systems have, of course, been considered in some depth as part of the concept design of the computer simulation system that will be outlined in the next section. This simulator will be developed extensively in the next phase of the project in order to study many aspects of communications and intelligence in a unified framework.

The following parts of this Section contain some general observations about work on intelligent signal processing and the central role that machine learning is expected to play

[6] The endocrine system is, of course, another important communications system in the body, but this comment refers only to the central nervous system.

in the development of appropriate processing techniques, and about communications systems for an ageless vehicle. The latter discussion emphasizes the desirability of parsimony and simplicity in network design.

7.2 Intelligent signal processing

Imagine a "living machine" (see Ref. 1) capable of real-time autonomous learning while interacting with its environment via multisensor data fusion (Hall and Llinas, 1997). Autonomous space vehicles of the future will doubtless use a combination of such example-based intelligence along with traditional rule-based intelligence (Jackson, 1999), relying not only on human input, but also on input from "more experienced" vehicles. One can also imagine a future where human input is not available; for example, a newly self-assembled deep space vehicle may have to decide for itself (or in collaboration with its self-assembled mates) what is worth knowing!

NASA is actively engaged in such research (Refs 4, 5), a key driver being the massive amount of data collected by space probes. This presents a major challenge:

How can this flood of data be converted into useful knowledge?

Machine Learning (Mitchell, 1997) is playing an increasingly important role in meeting this challenge (Mjolsness and DeCoste, 2000). An example is NASA's Autonomous Serendipitous Science Acquisition for Planets (ASSAP) project (Ref. 8) aimed at demonstrating on-board processing and autonomous target acquisition so that only scientific data of interest is relayed back to Earth. This addresses the problem of limited bandwidth, and at the same time increases the knowledge/dollar ratio – both important issues for NASA's New Millenium missions.

Although the signal processing requirements of the ageless vehicle sensing system have not yet been directly addressed within CTIP, we have a strong skill base in intelligent signal and image processing technologies of relevance to the project's goals, as demonstrated in a wide variety of applications, including:

- Transform and content-based image and video compression (Rees et al., 1997).
- Content-based search and retrieval in image databases (Rees et al., 1997).
- Real-time face detection and recognition. CTIP's SQIS (System for Quick Image Search) technology is now in the commercialization phase (Qiao et al., 2002).
- Speech and gesture recognition for device control and video games in Oz-IE (Australian Intelligent Environment), CTIP's smart room (Ho et al., 2000).
- Pattern recognition-based inversion of spectra for rapid mapping of solar magnetic fields for space weather prediction (Lopez et al., 2001).
- Multimodal sensing and decision systems for telehealth (Wilson et al., 2000).
- Knowledge-based image processing for automated medical diagnosis (Brown et al., 1998).

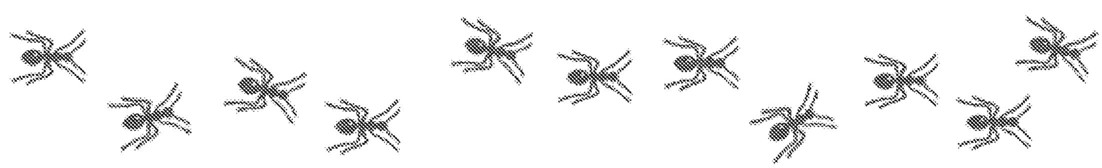
7.3 Communications

Designing a communications system for an ageless vehicle will not be a simple task. Along with other parts of the vehicle, such a system must partake of fundamental properties, which allow self-monitoring, self-maintenance, repair and replacement. At the same time the communications network must be able to robustly transfer any and all needed data within the vehicle, particularly fault-related data at all levels from the very local to the vehicle as a whole. Furthermore, it must be able to do this even when severe fault conditions are present, as there will always be a finite time between fault detection and repair. Other data transfers are also required, for condition monitoring as part of preventative maintenance and to flag possible future problems.

The approach taken to communications by biological systems has been discussed elsewhere in this report (Section 3). It is true to say that such systems tend to exhibit both **parsimony** and **simplicity** – that is, only what is needed is communicated, and that is done in the simplest possible manner. As a further example, the communications amongst ants in an ant colony has been described and modeled by British Telecom (BT) in an exercise which has yielded results which have been applied in several areas, including the design of robust telecommunications networks (Ref. 15). This may be briefly described as follows.

An ant colony is a miracle of organization, in which each ant knows its job, and keeps on doing it independently of all the other ants. The ant applies four simple rules in its task of food-gathering:

- If you find food, take it home, marking a trail to show your route between food and home.
- If you cross a trail and have no food, follow the food trail.
- If you return home with food, put it down and go back along the same trail.
- If the first three rules do not apply, wander about at random looking for food.

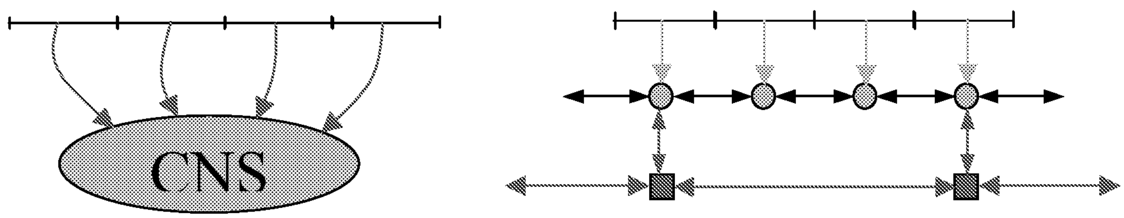


A computer program only five lines long can simulate these basic rules which keep the ant-colony operating smoothly – an excellent example of both parsimony and simplicity.

Centrally controlled or hierarchical networks?

Of course, an ant colony (at least in foraging mode) deals with damage by having lots of ants, and not worrying too much if a few are lost or damaged. The individual components of an ageless vehicle are more important because they have a local function (integrity, sensing, communications etc.), and need to be replaced if damaged. The communications system must be able to cope with this situation, so as well as being parsimonious and simple it must also be very **robust** and, like the ants, highly **redundant**.

How can networks be designed to be both robust and redundant? Architecture plays a large part, as can be seen by considering two extreme options, (a) central connection and control, where all parts communicate with a central hub, or (b) hierarchical, where the network is layered, and all communication within each layer is local. These scenarios are illustrated as follows.



CENTRAL LOCAL & HIERARCHICAL

Overall, systems that tend to be local and hierarchical will be more robust, since damage can be dealt with in the local region, and there is more scope for adaptive behaviour, where one part may take over the functions of another. However, this is balanced somewhat by the relatively slow communications speed of most hierarchical networks, where signals must be passed through a number of layers. It is probable that the optimum configuration in any given case lies somewhere between the two.

A third possibility is a distributed network, in which nodes (or agents) are connected to others at random, irrespective of physical separation or node functionality. Thus there is a specific probability that any particular node is connected to any other in the system. Such networks are more robust to damage than central, or local and hierarchical, networks, but the price paid for this is more complicated communication paths. The internet is a distributed network of sorts, but it is not a "pure" random distributed network. It is characterized as a scale-free network (see, e.g., Cohen, 2002, Albert and Barabási, 2002). Such networks have been identified in a wide range of situations, from sociological to biological, in which the network topology is influenced by network growth and evolution.

A further question is whether communications should be synchronous or asynchronous. In a network where robustness is a factor, asynchronous communications would seem to be best, although self-synchronizing behaviour within local networks is an intriguing possibility which may well have practical consequences, one of which is mentioned in the next section.

Processing

There will be cases, depending on particular sensors and required information, when it will be either desirable or necessary to use data from a number of sensors to obtain information about the occurrence or location of an event. This could occur, for example, if an array of strain sensors was used to determine the location of a surface impact. Another example is given in subsection 8.5. In such cases it will be necessary to strike a balance between processing that is carried out locally at the site of each sensor, and processing that uses data or information gathered from a number of sensors in a region. In general there will be a balance between local, regional and global data processing.

The processing required, and the distribution of the processing, both spatially and between hierarchical layers, cannot be determined without knowledge of the communications links used, the algorithms to be implemented and the power budget. Where power is limited it is important to know the relative costs of transmitting data and processing data. For short distance wireless communication links, using current technologies (Ref. 18), the energy required to send a single bit is 100 to 10,000 times the energy required to process an instruction. This has implications for the extent to which data is processed locally or in a more distributed fashion.

The network as a sensor

Any communications network, particularly one that is self-monitoring and communicates locally, can act as a sensor network in its own right, without the need for additional physical sensors. This is analogous to a rudimentary "pain" sensor, and can happen provided that each element is capable of detecting the absence of expected "I'm all right" signals from its immediate neighbours. In fact, this process is quite similar to the way the human body responds to and communicates damage. Changes in the self-synchronization of local groups of elements could be a sensitive way of exploiting this property, which can be implemented on several scales.

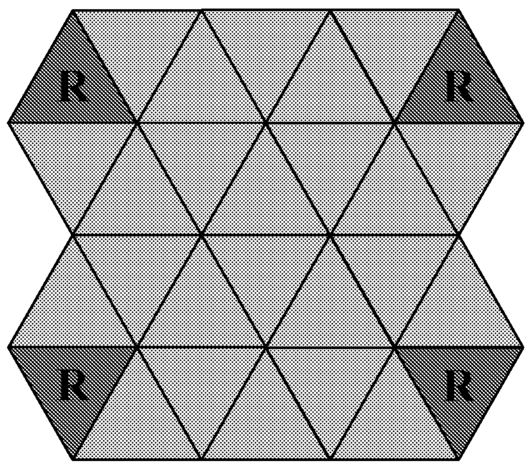
The network as a complex system

The hierarchical interacting systems under discussion are highly nonlinear and therefore may be described as complex systems. As such, emergent properties are to be expected and perhaps designed for. Self-synchronized local areas as described above could be one example of such behaviour.

The simulator and communications

The tiled simulator discussed in this report (Section 8) uses local communications, albeit so far only in a single layer. Very little work has as yet been done on communications issues. However, the simulator is the ideal test-bed for experimentation on hierarchical, locally-communicating networks, and it is envisaged that this will receive significant attention in the next stage of the process. In this area there are currently more problems than solutions, but CSIRO has a broad expertise in communications networks that can be brought to bear on the problem.

Following the criteria of simplicity and parsimony, it is proposed that initial experiments look at a very basic locally-connected network (like the current tiled simulator), concentrating on its ability to act as a pain sensor. Signals should be limited to the minimum possible – perhaps just two are needed, a simple handshaking between adjacent tiles ("I'm OK") and a fault message ("Something's wrong"). Asynchronous communication should be used, but the possibility of useful self-synchronization should be investigated. The following diagram shows schematically what is intended.



R = Reporting Centres

As a first step the current single-layer structure should be retained, except for distributed "reporting centres" which collate signals and act as a transfer mechanism to a (nonexistent) second layer. Initial tests will seek to determine the ability of the network to detect, locate and report damage. This could lead naturally to the inclusion of data from other sensors and the investigation of intelligent behaviour as discussed in Section 6.

As well as amalgamation of such a communications network into the tiled simulator (Section 8), it would be valuable to carry out a set of independent simulations on the communication network itself, seeking to optimize functionality whilst satisfying the virtues of simplicity, parsimony, robustness and redundancy.

Further discussions of communications requirements are contained in the next section, on computer simulations, where consideration is given to adaptability of the network, and robustness to both damage and overload.

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8. Computer Simulation

8.1 Introduction

Computer simulation is a powerful tool for testing concepts and systems in a multitude of potential situations and environments. When anticipated environments and situations are too difficult or too expensive to create in real life, simulation may provide the only means of evaluating the behaviour of the system. Real environments can, of course, be difficult or impossible to model accurately (e.g. complex atmospheric effects), but a simulation of the response of a system in a model environment can yield valuable insights into its behaviour under real circumstances. A unique advantage of simulators is their ability to simulate materials and technologies that do not yet exist, which can be extremely useful for modelling futuristic systems.

The aim of the work described in this section has been to begin the development of simulation software that will enable the behaviours of various models for the intelligent sensing system of an ageless vehicle to be studied. Conceptually, there are a very large number of combinations of material, sensor, communications and intelligence paradigms that could be employed in the design of a potentially ageless vehicle. Rather than restrict consideration to a small subset of these combinations, the objective of this work has been to develop a sufficiently flexible architecture to ensure that virtually any concept can be tested on the simulator. The simulator could be used to test concepts at an abstract level, or to analyse the complex behaviour of an entire ageless system.

The ultimate usefulness of a computational simulator depends on how accurately it can model the various components of the system being studied, or on how well it can capture the essential features of the system. This requires modelling of the external environment and its effect on the vehicle, the response to the environment (both internal and external to the vehicle) of the materials of the vehicle and the sensors, the data processing, communications and decision-making systems, and the effect of the actions resulting from these decisions on the vehicle and, in turn, on the environment. A complete simulation may be extremely complex.

The work so far has concentrated on the development of a flexible architecture for simulating a surface or skin of a vehicle, with sensors and an intelligent data analysis and decision-making system. It does not yet include a model for the external environment, though simple environmental effects, such as the incidence of small impacts, could be included in a straightforward manner. It does not yet include details of sensor response to an environmental perturbation, though, again, a simple response to simple events could be included readily. It is possible that increasingly more complex and realistic models of these features can be implemented as the simulator is developed further. The initial aim is to study the behaviours of different structures of the intelligent data processing, communications and decision-making system for simple inputs from the sensors.

Ultimately, the concept demonstrator (see Section 9) will be used as a hardware test-bed to experimentally verify simulation results.

This section begins by giving a general overview of the various types of simulations that are possible, and what sorts of simulation might be useful in this project. Details of the simulator code developed so far are discussed. The desired properties of our ideal simulation tools are listed, and finally suggestions are made about what needs to be addressed and where the research should continue.

8.2 Principles of the simulator

The first requirement of a simulator is a definition of the system to be modeled. In this case, the structural system is based on the model structure proposed in Section 2. This is a modular skin, in which the modules may be thought of as “scales” or “tiles”. Each module may contain sensors, a processor unit and memory, communications capability and an energy store. Other capabilities can be readily implemented. The simulator was originally based on the triangular tiles model proposed in subsection 4.4 and described in more detail in Appendix A4.1, but tiles of any shape and configuration can be modelled. Figure 8.1 is a schematic diagram of a contiguous array of triangular tiles. Hierarchies of tiles, with higher levels being known as “supertiles”, can be established either statically (i.e. in a pre-determined arrangement) or dynamically according to requirements. This is discussed later in this section.

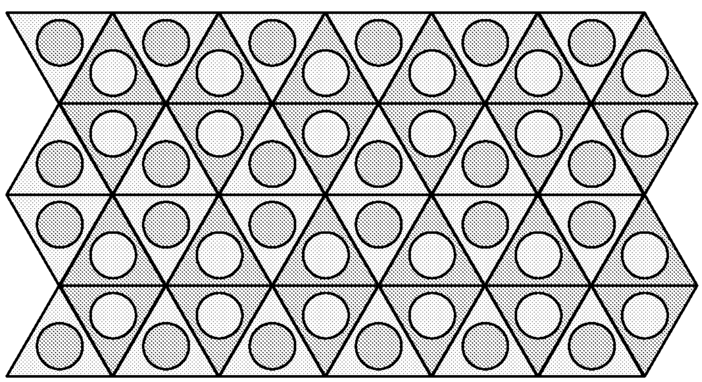

Figure 8.1: A schematic diagram of an array of triangular modules (tiles) that might form an internal surface or part of the skin of a vehicle. The circular structure on each triangular module represents the sensing, processing and communicating capability of the tile.

<u>Scope of the simulation</u>

This project is concerned with the development of integrated vehicle health monitoring systems, so it should be remembered that the main purpose of the simulation is to provide a tool for assessing the effects of different measurement, data processing, communication and decision-making strategies. Other issues such as material properties and repair strategies are not the core concern of this work. At least in the first instance, the effect of the external environment, or the immediate environment of the panel or component being modeled, is simply to produce a set of sensor responses.

In a complex system such as this, with its many different possible options, variables, topologies, environments, etc., it is important to be clear about exactly what information is required from the simulator. Which outputs, inputs, and variables are desirable for the simulation in the first instance? What might be desirable for future versions? These quantities define the scope of the simulation, and will be discussed below.

Scale of the simulation

This basic model can be used to simulate any part or parts of a vehicle, such as:

- detailed panel sections consisting of finite elements;
- bulk parameters that describe general performance (e.g. a module may represent a whole vehicle component); or
- a whole vehicle.

An important question, which can probably only be answered experimentally, is related to the number of modules ("tiles") that should be included in a simulation. If a detailed panel analysis is performed, how many modules should be simulated? For example, for a vehicle the size of a space shuttle with each tile about 10 cm x10 cm, there will be of the order of 4000 tiles on one surface of one wing. We will assume (or define) that this part of the vehicle is essentially self-contained in terms of the self-repair system of the vehicle, and is representative in its system behaviour of other such segments of the vehicle. It is proposed that initial simulations, applicable to the concept demonstrator (Section 9), be performed using something like this number of tiles.

If the number of elements in the simulation reaches tens of thousands, it is likely to be possible (and more computationally efficient) to perform bulk statistical analysis rather than finite element analysis to check the resulting system trends. This is something to consider for future work, after experimentation and small-scale simulation have provided a feel for how a specific system behaves.

Types of simulation

The following different types of simulations might be performed.

- Time-based simulation, in which variables are propagated forward in time.
- Frequency-based simulation, in which variables are determined over a range of frequencies.
- Spatial simulation, in which variables (perhaps steady state?) are propagated over the physical dimensions of the object under simulation.
- Scenario simulations. These are similar to ensemble simulations in quantum physics: perhaps the probability of a particular outcome is to be determined for different environments/system parameters (scenarios). This might allow for optimization of the system to minimize the risk of unfavourable outcomes. System stability could also be checked.

These types are not necessarily independent. The outcome being studied in a scenario simulation might be the result of any of the first three simulation types.

Method of simulation

In any type or scale of simulation, the machinery that does the calculation and propagates the values under simulation forward may be deterministic, statistical, or some mixture of the two. Calculation of the next value may depend on an algorithm (employing a numerical approximation or an analytic solution), or arithmetic/logic functions, or it may be determined by intelligent reasoning. This must be the case in order that the various functions of the sensing system are simulated. It should be expected that, for a given set of initial conditions and set of parameters, there might be a non-unique outcome.

8.3 Inputs and outputs

The following are suggestions for quantities that might be of interest to measure, given a particular system design, parameters and environment. These are simulator outputs.

- Speed of reaction of the system to damage or other stimuli.
- Rate of resource usage (energy, material, etc.).
- Lifetime of system (needs definition of end of life criteria, e.g. death of 50% of tiles, loss of a certain proportion of functionality, etc.).
- What rate/area of damage can a given system recover from?
- Where do energy, materials, communications flow?
- Accuracy of the system's knowledge of its environment and own status.
- Properties of the emergent behaviour of a system of agents.

The following are all simulator inputs.

a) Different system designs in order to simulate:

- Tiles that can move around, repair, form logical hierarchies (supertiles).
- Material, energy and information flows between regions.
- Tensegrity structures.

b) Different system parameters to simulate the effects of:

- Tile density (size and total number) for a given vehicle.
- Number of hierarchy levels and number of tiles in each level.
- Different functionality and responsibility at different levels of the hierarchy.
- Algorithms implemented by each tile. Each tile must use some logic in deciding what to do with its sensor information, resources, what to communicate and with whom, etc. This algorithm, which performs the local signal processing, is probably the most important entity in the whole ageless system.

c) Different environments to simulate:

- Meteor or radiation storms. Parameters might include impact rate or incident flux, size/energy, location of impact, and the area of damage.

- Energy and material availability: what happens when the ageless system is starved of energy or spare parts?
- Communication noise: what happens when information can't get through or is corrupted?

8.4 Details of present development of the simulator code

Overview

Code has been developed to represent an array of triangular tiles such as that shown schematically in Figure 8.1. The shapes and capabilities of the tiles, and their interactions with neighbouring tiles, can be defined. In particular, the following has been achieved at this time.

- A Visual C++ object framework has been constructed, based on the modular tiles idea, but it is sufficiently general to also model other concepts. It is a time-based state machine.
- Modules or tiles, referred to in the software implementation as "SmartUnits", can be constructed, each from arbitrary combinations of sensor units, logic units, mobility units and a single energy source.
- In general, many events occur in parallel, so the simulation has a (non-real-time) clock, and all events have a defined duration. The simulation is a state machine that sweeps through all of the elements of the system and updates their state on a regular basis. Since the next state is dependent only upon the current state and current inputs, the order of up-dating the simulation elements during the sweep is not important. The decision about what is the next state of each element is not simple, and depends upon a complicated algorithm.
- A simple test program that exercises this simulation framework is being used to debug the code. It creates a small finite plane of tiles, inflicts damage, and displays the tiles on the screen with colour-coded responses.
- Software development is proceeding satisfactorily: code defining the tiles (SmartUnits) is in place, and debugging using the test program is well advanced.

Design

The fundamental components or attributes of a single module/tile, or **SmartUnit**, are:

- Structure – physical shape.
- Logic – ability to process sensed values, make a decision and perform useful tasks.
- Sensors – obtain readings from the environment and reliably interpret the data.
- Communications – read and write values for interaction with neighbouring agents.
- Energy – a source of energy to perform tasks such as processing logic or moving.
- Mobility – move within the environment (this ability is optional and could possibly be encapsulated into the structure component).

The **SmartUnit** is the software representation of a tile, to which the various attributes listed above may be attached. A SmartUnit has a physical shape but cannot perform any intelligent behaviour alone (at the current stage of development). The SmartUnits may be damaged: when random damage occurs, the SmartUnit's physical appearance may be altered and all components attached to it may also be damaged.

In order to relate this discussion to that of the intelligence issues (Section 6), the SmartUnits will be identified with the autonomous agents of an intelligent system. Thus, a tile can be thought of as an autonomous agent in the physical system, whether it is an entire vehicle or a sub-component.

Logic

Various agent logic-modelling tools have been developed (see, for example Wooldridge, 1992; Giese, 2001) to test the reliability of various logical systems in the study of emergent behaviours and many other aspects of intelligence.

Sensors

At present a sensor is represented as a register, which contains a real number that can be set and read in a user-defined manner. Noise on the sensor is represented by an addition to the sensor value of the product of a fractional ambient noise level, the maximum sensor value, and a random noise percentage. Other sensor implementations may require other definitions of noise to match the sensor type. More sophisticated models of sensor responses may be incorporated later.

Communications

The method for propagation of information throughout the system, allowing for joint-belief decision-making and other high-level information interpretation, requires a communications protocol and a medium. Agent-based communication in an ageless vehicle could be realized in many forms and as such the communications unit has been left reasonably abstract. The "TransmitData" command places a string of values on the transmit buffer which can then be read by other SmartUnits. "ReceiveData" places a string of values on the receive buffer which can be read by the internal logic unit. This enables any communications system to be implemented, ranging from direct (wired) connections to wireless communications such as IR and RF. Dynamic reconfiguration of the communications as an emergent behaviour of the system of agents is discussed in the next subsection.

Energy

Each SmartUnit has a source of energy known as the energy unit. Each operation such as processing logic, reading sensor values or moving mechanisms on the unit will deplete the energy unit by a certain amount. When the energy unit is fully depleted, these actions can no longer be performed. The energy unit has a maximum storage value. A future enhancement will be to limit the maximum amount of energy transferred per second (i.e. power). Damage to the energy unit will always result in a decrease of available energy and possibly reduce the maximum storage value.

Mobility

An agent may have a number of methods for moving within the environment. Typically, movement is achieved through actuators and so the mobility unit attempts to provide a general representation of this hardware. As is the case for communications, a high degree of abstractness is required and so only the Move operation is provided, to be consistent with all forms of mobility. Damage to the mobility unit can result in the SmartUnit arriving at an incorrect location.

The effects of damage and noise

When smart agents are realized in a physical (tile) form, additional physical factors will determine how an agent reacts to external stimuli. Cells in the human body can be considered as autonomous agents in the sense that they have objectives to achieve and their actions appear relatively autonomous (i.e. each response is not directly controlled by some external entity). Interestingly, external influences such as radiation, viruses, extraneous environmental conditions and the like can cause damage to the physical structure of the cells, sometimes causing the cells to become cancerous. A cancerous cell does not perform the duties of a normal cell, and by this inaction, further damage to the system or other cells can be caused. Even more hazardous is a cell performing malicious actions such as attacking healthy cells and causing them to become cancerous. It is possible that their non-biological counterparts could be susceptible to similar dangerous behaviour. Regardless of whether viral behaviours emerge, at the very least physical damage *will* alter the agent's internal representation of the external environment.

In many simulations of autonomous agents, cancerous effects and incorrect logic are overlooked. In a physical implementation of a community of autonomous agents, where human safety is required, a risk assessment of the possibility that cancerous behaviour could emerge should be considered.

It is proposed that the logic unit of a SmartUnit be implemented with a damageable RAM and CPU clock. This will allow the simulation of physical damage to the RAM, causing register values to be lost or corrupted. A more realistic simulation would allow for the CPU instruction set to be damageable, but this would require the software implementation of a CPU architecture and is therefore left as a future enhancement.

The logic unit currently executes a static code sequence, and will store values in the local SmartUnit RAM. Before the logic code is executed, the sensor readings are updated. The reading may have noise or be incorrect depending on the damage levels of the particular sensor. The logic unit can output voltages to actuate motors or write to communications buffers.

It is likely that the logic hardware and software of an ageless vehicle will require up-grading, to allow it to learn, to allow its behaviour to evolve, and to improve its resistance to damage. In some circumstances this might be achievable as maintenance up-grades, but probably not in general. Evolving software is already under active investigation and some developments in evolving electronic design have begun (Thompson et al., 1999).

The concept of evolvable hardware has been discussed (e.g. Toormarian, 2001), and may be applicable to both structural and logical hardware.

8.5 Simulating an intelligent system

Adaptability, coordination and representation

An ultimate goal of this work is to simulate the following fundamental and critical capabilities.

- The development of a concise representation of the state of damage.
- The selection of a coordinated and adaptive strategy for dealing with the damage (e.g., coordination of SmartUnits, prioritization of repair, mitigation of further damage via re-configuration of SmartUnits).

Therefore, it is important to analyze the components of a **SmartUnit** in terms of these capabilities and potential constraints.

Structure

- The shape of each SmartUnit (tile) may change, e.g. as a result of impact (injury response).
- Spatial overlapping of SmartUnits may be another option (not unlike multiple cell layers where exterior cells may cover lower exposed cells), which could be used in morphing solar panels, radars, etc.

Logic

- Software may adapt (assuming the hardware has an ability to do so, and information about this ability is available) as a result of new observations.
- Adapted ("learnt") logic may be transferred to other tiles, potentially to a central (or distributed) store.

Sensors

- Thresholds may change in order to detect different quantities, dependent on evaluated damage and any configuration changes.

Communications

- More links can be activated to determine the state of surrounding SmartUnits (tiles), e.g. the extent of impact damage.
- Information can be gathered/sent via dynamic connections, varying locally and globally (e.g. using a remote central or local hub source), dependent on available hardware.
- Communication links can be re-configured.
- The logical structure of the communication network may not necessarily be two-dimensional: it may be better understood as a higher dimensional structure, with the underlying (hardware) communication structure being a two-dimensional projection (as, for example, is the case with Penrose tilings). In other words, if

one pathway is often used, the network can perhaps change to create a faster more direct link using a shorter path in the higher dimensional space.

Energy

- Energy can be transferred via flexible routes: from neighbours, or from central store(s).
- The rate of energy usage may change, dependent on damage and system reconfiguration.
- Levels of initial energy may vary depending on hardware needs.

Mobility

- SmartUnits (tiles) may have an ability to flip, move, re-configure and interact with other tiles.

Emergent behaviour

There are a number of reasons to study and simulate emergent behaviour (see, e.g., Section 6). Here we highlight particular aspects related to communication and re-configuration.

1) No communication network can afford to transmit *all* information *all* the time. However, it is inherently dangerous to allow individual tiles to decide which information is significant and which is not, because a single sensing unit cannot interpret its sensed data in the context of the overall vehicle. Thus, the "I don't communicate unless I have something interesting to report" approach may regard the slightest wind perturbation as trivial, and so does not communicate this information upward. However, if units over a large area all experience the same minute perturbation, it might indicate a gentle breeze from the north (which might be useful information). If each unit had decided that this minute perturbation was not sufficiently interesting to report, then the more abstract interpretation of "a gentle breeze" could not have been formed.

   To take account of all information received, and avoid communication overload, a hierarchical topology, in which the higher layers represent increasingly abstract information, can be utilized. Here is a simple example that may help illustrate the point. At the lowest level, the information presented may be "pressure change to 102 kPa". The next level may then say, "lots of tiles on this face have detected a pressure change and the average is now 102.7 kPa", and the next level concludes, "there is a gentle wind from the north". The data is being transformed successively to more abstract information and knowledge as communication proceeds to higher levels.

   The amount of information a tile should communicate can be decided with some input from (or inhibition by) a "higher" level, after a pattern or dependency has been established. A precise form of such a hierarchical topology should not be pre-programmed but rather emerge from interaction among the SmartUnits (tiles); neurons provide a basic biological analogue of this. We may illustrate this point with the "supertiles" concept, as depicted in Figure 8.2. Supertiles are a logical connection of two or more tiles, and have greater communication ability and a higher level of information and processing ability.

2) Tiles should have some form of self-assessment. This could be achieved through a redundant or alternate self-checking sensor, or via joint beliefs of neighbouring tiles in a supertile.

3) Supertiles may provide the next level required for a coordinated response: a local pattern is established and actions at the tile level are initiated, propagating to a higher level, depending on the importance. It is necessary to avoid fixed hierarchical control, by enabling the tiles to reconfigure back to smaller (super) tiles.

4) Self-similarity is one of the important characteristics of (chaotic/fractal) complexity. Therefore, the next logical layer could or should have the same shape (see Figure 8.2). However, different sized supertiles may emerge, with any overlap being dependent on required functionality.

5) Learning from emergent behaviour or actions may result in more persistent reconfigurations, optimising performance or response.

A particular emergent behaviour for a system of agents results from the particular selection of an agent's rule set. Currently, there is no known systematic way of theoretically predicting an agent rule set from a desired emergent behaviour. The reverse problem, theoretical prediction of emergent behaviour given a set of rules for each agent, is also difficult, and simulation should be performed. It will be necessary to develop an extensive mathematical basis for analyzing the system, and tools for design and prediction will be required. Current theory in this area is not adequate.

<u>*Biological analogues*</u>

Genetic evolution

Evolution could be governed by:

- Measuring survivability. This could be used as the "fitness" function. How long does it survive after an impact?
- Measuring adaptability. If a tile is hit, the system should still be able to continue communication (via an alternate path or different communication method).

Repair mechanism

The repair mechanism may mimic biological methods, with a temporary fast-fix followed by a slower, more permanent repair (as is discussed in Sections 3 and 5). Actual communication may also have to exhibit this behaviour, by using an alternative logic for communication when tiles are damaged, and returning to optimal/normal communication when the tiles (and communication pathways) have been restored.

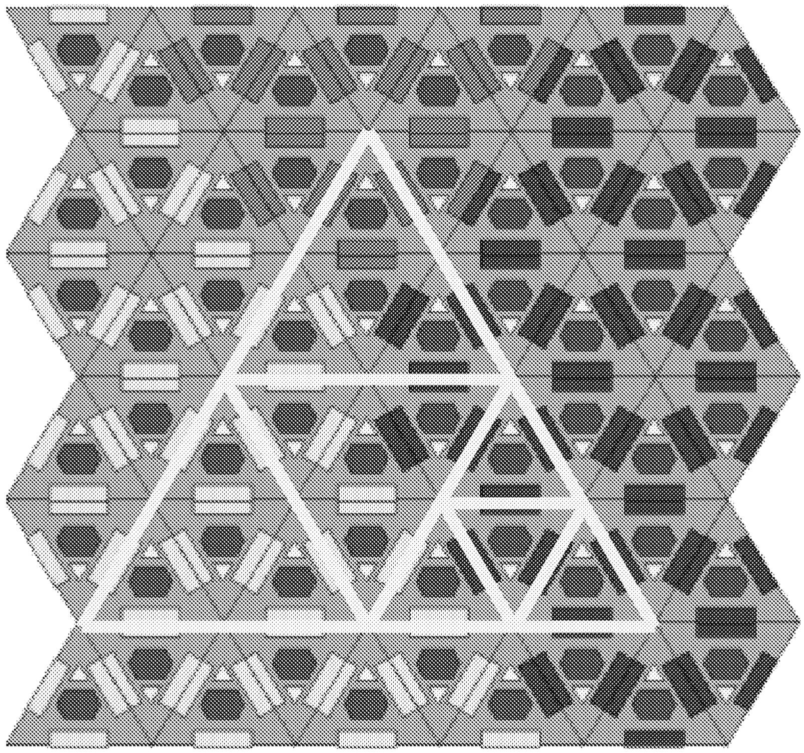

Figure 8.2: A block of 60 triangular tiles, showing the communications connections as rectangular boxes along the edges of the triangles, the sensors and logic units as the brown hexagons, and the energy store as the light triangle in each tile. The different colours of the communications links indicate different values of the information being exchanged. The yellow triangular outlines indicate some possible configurations of supertiles.

Tile factory

When two successful tiles “mate”, the information required to produce the progeny (cf. DNA) could be sent to a “tile factory” for production rather than the tiles requiring the ability to procreate. In addition to the basic instructions for tile production, as could be encoded in a DNA-like recipe, the ability to pass on learnt information to other tiles could lead to faster convergence of desired behaviours in the replacement tiles, and possibly improved cognitive processing. This is analogous to whales teaching their young to hunt, rather than relying on (DNA-encoded) instinct.

8.6 Further development of the simulator

Some software developments that should be carried out during the next phase of the project to get the simulator to a point where it is useful for analysis of real systems are listed below.

1) So far only the 2-dimensional case of flat tiles has been studied. The code framework supports further dimensions, but implementation of this has not yet been done. Additional code is required to handle:
    - closed surfaces such as cylinders and spheres;
    - solid 3D matrices of tiles;
    - edges and realistic boundary conditions.

2) Some elementary logic has been tested, but the simulation of a design relating to a real and practical system is yet to be performed. It is intended that many of the concepts discussed in this report will be drawn upon, and simplistic through to accurate representations of these concepts will be modelled, and tested in virtual hazardous environments.

3) The simulator graphical user interface (GUI) should be extended to allow multiple views. For example, there can be one view to monitor power flow, another view for communication flow, another view to show units that have updated their logic (learned), etc.

4) Once a feel has been obtained for small-scale behaviour of the system, and correctness of the tile algorithm is proven, perhaps a statistical simulation of a larger system could be designed.

8.7 Concluding comment

The simulator is a test-bed of new ideas, and therefore should be as general and unrestricted as possible. The physical concept demonstrator (Section 9) will be a physical manifestation of some ageless system ideas, but it will be limited to what can be implemented using current materials and technologies. These two test tools, the simulator and demonstrator, should feed off one another by checking each other's validity and incrementally increasing the complexity of the system.

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9. Proposal for Development of a Concept Demonstrator

One of the major objectives of the next phase of this project is to design and complete the first stage of a concept demonstrator. The concept demonstrator is envisaged to be a combined hardware and software system that will, ultimately, be capable of demonstrating principles of an intelligent vehicle health monitoring system. Details of the design of the demonstrator will be worked out later, but the purpose of this section is to present a proposal for the general aims and principles of the demonstrator.

One of the main benefits of the concept demonstrator will be to act as an experimental test-bed for results obtained from the computer simulator described in the last section (Section 8). More specifically, the goals of the concept demonstrator should include the evaluation of physical sensors, processing and communication strategies, and agent implementation. Computer simulation, being relatively fast and versatile, provides the opportunity to study systems with a wide variety of characteristics, from different environments, threats and sensors, to different tile configurations, communications topologies, different data processing algorithms and different characteristics of the organization and interactions of the intelligent agents. As was noted in the last section, the availability of both a computer simulator and a compatible concept demonstrator provides a very powerful set of tools for studying an intelligent sensing system.

The general philosophy is to regard the development of the concept demonstrator as a multi-year project, but with the development staged in such a way that significant milestones are achieved each year. Appropriate milestones will be decided, in consultation with NASA, on a year-by-year basis, depending on progress during the preceding year.

The ultimate goals for the demonstrator are to demonstrate an ability to form a concise representation (perception, awareness) of the state of the structure, to develop flexible strategies for repair of damage and mitigation of further damage, and to demonstrate an ability to learn from past experiences. The demonstrator should operate in a simple environment containing only a small number of different threats, but the frequency, severity and number of potentially damaging events may be large. The demonstrator should be as simple as possible, consistent with the stated goals. Initial objectives for it do not include development of new or realistic fabrication or miniaturization techniques, or new hardware developments.

General characteristics of a suitable concept demonstrator

The general characteristics of a suitable concept demonstrator should include the following.

1. It should be capable of demonstrating principles of an integrated intelligent sensing system, i.e. sensing by a large number of sensors, data processing (at local, regional and global levels), adaptive communications and networking, and intelligent decision-making. It should address an issue of concern to NASA.

2. It should concentrate on the aspects of a sensing system in which CSIRO has strengths: integrated system design, data processing, networking, communications and intelligence. CTIP's knowledge of sensors and measurement techniques, and the use of that knowledge in the development of an integrated system, is more important in this context (in fact it is of central importance) than our expertise in sensor development. It would be attractive, of course, if examples of CSIRO and NASA sensor technology could be included in the demonstrator, but this should be viewed as a desirable rather than a necessary outcome.

3. It should be based on a simple structure.

4. It should be capable of being upgraded in future years to enable the demonstration of more sophisticated concepts.

5. It should be a well-engineered, convincing demonstrator.

Proposed characteristics

It is proposed that the prime aim of the demonstrator should be to detect, locate and, as far as possible, characterize surface impacts. This is a significant current problem, and was identified as such in Section 5 of this report. General characteristics of the demonstrator could be as follows.

- The structure could be a flat plate or, preferably, an enclosed structure such as a cylinder. A cylinder with removable end-caps would allow access to both sides of the skin, and the cylindrical surface could be fabricated readily as a single piece or as hexagonal or triangular modules (tiles). A sphere (perhaps geodesic) has some attractions, but access to the inside surface of the skin may be more limited (depending on the size and design of the structure).

- The sensors are proposed to be surface-mounted strain gauges, capable of measuring small surface strains with frequency components up to about 1 MHz. These sensors could be used at a later stage of development to detect acoustic emissions produced by events such as cracking or leaks. Possible sensor candidates include thin-film strain gauges, piezoelectric patches (thin-film ceramic or PVDF sheet), nano-particle strain gauges and optical strain sensors (optical fibre Bragg gratings, optical interferometry, etc.).

- Temperature and pressure sensors, sensor functionality and network continuity checking could also be used to provide complementary information.

- A large number (~1000) of sensors should be used.

- A flexible and reconfigurable communications topology.

- The initial aim would be to have the system demonstrate an awareness of the locations and severities of multiple impacts by utilizing the information from a large number of sensors. Perhaps it should be capable of making a rudimentary repair/ignore decision, or a prioritization of responses to the various impacts. Added (realistic) complexity is provided in this case by the fact that the sensors detect acoustic (or elastic) emissions from other sources, many of which are normal and harmless, and by elastic reverberations within the structure. There will be challenges for intelligent signal processing. This is recognised as an important problem in vehicle health monitoring, but it need not be solved in its full complexity in the first phase of the demonstrator.

- The development path in future years could include the use of optical imaging techniques for damage assessment, including assessment of surface degradation, the development of active elastic surface wave detection methods for characterization of impact craters, increasing the complexity of the acoustic emission background and the addition of other threats (leaks, pressure loss, fatigue, cracking, …). These developments would increase the amount of information available about damage, but would also increase the complexity of the data fusion and processing tasks.

- The major developments in future years would be aimed at improving the intelligence of the system. The other developments listed above would increase the need for improved intelligence, and provide opportunities to demonstrate it.

10. Summary and Conclusions

This report has canvassed a number of issues involved in the development of an intelligent health monitoring system for a future ageless aerospace vehicle. In almost all areas, analogies with biological materials, structures, processes and behaviours were employed extensively to provide insight and inspiration, even in cases where biological solutions were recognised to be less that totally adequate or appropriate to the requirements of an ageless vehicle. Such cases include the relatively vulnerable structure of the mammalian central nervous system, and the immense complexity of the human blood clotting mechanism.

It was not possible, given the time available, the current state of knowledge in some areas, and the depth of our understanding of some issues, to draw any firm conclusions about the eventual structure of such an intelligent sensing system. In any case, important details will depend on unknowns such as the properties and capabilities of materials, self-repair mechanisms, and available sensing, communication and computational technologies. Nevertheless, the discussions have indicated some general directions that appear more likely to be useful than others. These include the following:

1. To repeat an observation made in Report 1 (CTIP, 2002), it seems likely that, whatever the capabilities of the materials for self-repair or regeneration, there will be a requirement for knowledge of the occurrence and nature of the damage to be communicated to some region of the structure remote from the damage site. Thus, however advanced materials and structures become, there is expected to be a requirement for an integrated health monitoring system.

2. Temporary responses to damage will be important to combat rapidly occurring damage or rapidly escalating damage. Such responses might include:
   - redundancy by component duplication of structural over-engineering;
   - multi-stage repair processes;
   - isolation, and in some cases sacrifice, of a damaged component or structural section.

3. Real-time continuous monitoring of structural health will present opportunities for more effective use of materials and more efficient structures. It will require sensing solutions that may, in some cases, differ significantly from those commonly used currently for non-destructive evaluation. Fixed, embedded sensors will often be preferred to mobile or scanning sensors. Embedded strain (or acoustic emission) sensors, particularly if implemented in MEMS or nano-technologies, have the potential to be extremely valuable for many applications of material and structural sensing. Some important sensing issues that should be addressed include:
   - development of strain gauge sensors suitable for surface mounting or embedding within a material, and processing techniques to enable extraction

of the wealth of information contained in continuously monitored elastic wave sensors;
  - long-term reliability and accuracy of embedded sensors, including issues of calibration, self-checking and self-repair for sensors and the network;
  - development of techniques, using either embedded or mobile sensors, for detecting and evaluating various forms of material degradation, in a range of materials;
  - effective self-testing diagnostics for control, navigation, communications and power systems; and
  - continuous selective chemical sensing in a range of gases and liquids.

4. There is a strong preference for implementing the system intelligence as a multi-agent system, on the grounds of both convenience of implementation (individual agents will be less complex to implement than an entire centralized system) and robustness. There is very likely to be some hierarchical structure among the agents, which may be fixed and pre-determined, dynamic with assignments determined by direct rules, or emergent. A great deal of fundamental research is required for the development of an intelligent multi-agent system, particularly in the areas of:
   - coordination in multi-agent systems;
   - learning, in intelligent agents and in multi-agent systems; and
   - the representation of data, information and knowledge.

5. The communications system will need to be parsimonious (minimum communication traffic) and simple in architecture (initially locally-connected). It will need to be dynamically reconfigurable for robustness against both damage and communications overload. The network topology will need to learn how to achieve optimal performance in circumstances of particular threats. This is likely to be achieved as an emergent behaviour of the system of agents. As is the case for the sensors, long-term reliability and reparability of the communications network is required. The communications network itself may be employed as a damage sensor, as long as it is sufficiently reliable that its most likely source of malfunction is damage to the vehicle structure.

6. Data processing, the key steps involved in converting sensor data to information, is an area of critical importance. Processing will need to be carried out on multiple levels, depending on the type of sensor and the information required. Local processing, at the sensor site, can provide local information. Regional or global information can generally only be obtained from data or information from a number of sensors: a single sensing unit cannot interpret its data in the context of a larger region or the whole vehicle. In some cases regional or global information will be obtainable from the information (i.e. reduced data) provided by a group of sensors, but in others the raw data from a spatial array of sensors may be required. An example of this latter requirement may be the use of a group of acoustic emission sensors as a synthetic array to determine the location of an impact, or to distinguish an impact from other sources of noise. These multi-level processing requirements have implications not only for the processing algorithms, but also for the communications network.

7. The multi-level requirements for data processing serve to reinforce the notion that an integrated approach must be taken to the development of the "intelligent system". Intelligence and learning ability must be embedded into all aspects of the system, and the system must be able to reconfigure or change its behaviour in response to, or in anticipation of, different sets of circumstances.

There are major research issues to be solved in all aspects of the development of an intelligent health monitoring system. We propose to develop two tools to enable some of these to be studied. The first is a versatile software simulator, capable of modelling many of the aspects of the intelligent sensing system of an ageless vehicle. It will have a sufficiently flexible architecture to allow a wide variety of concepts of material, sensor, communications and intelligence paradigms to be tested. The basic structure of this simulator has been designed and written.

The second tool is a hardware model that is simple in scope, but with sufficient capability to allow models and behaviours studied with the software simulator to be tested and demonstrated. The proposed demonstrator will initially be designed to detect, locate and characterize surface impacts such as might be produced by fast micro-meteoroids in space. This combination of simulation and experiment should provide a powerful research facility for studying the performance and behaviour of integrated health monitoring systems.

A final point is a salutary reminder, by a man who has clearly thought long and deeply about this problem, that the task of producing an ageless space vehicle must never be underestimated. Appendix A10 contains his words of wisdom.

Reference

CTIP (2002) *Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles: Threats and Measurands*. CSIRO Telecommunications and Industrial Physics. NASA CR-2002-211772, July 2002.

A4. Appendix to Section 4: Materials and Structures

This appendix contains material generated or discussed by the Materials and Structures Working Group, which is relevant to but not central to the discussion in the main body of the report. This material is generally of a more speculative nature. The subjects covered here are as follows.

A4.1 Self-assembling interconnected tiles

Introduction

The primary concept is for a small quasi-autonomous unit cell, with communications and power connections to neighbours. The cells are rigid (typically triangular) tiles which have the ability to perform computation, data transfer, sensing, actuation and, to a limited extent, movement. The intention is that a small sub-system of the tiles, supplied with a box of unallocated tiles, could, under program control, self assemble a large rigid array of sensors or transducers, or even just a physical structure. The tile-based system permits automated reconfiguration of the physical and functional structure. The limited mobility allows not only construction of systems, but also repair of damaged elements.

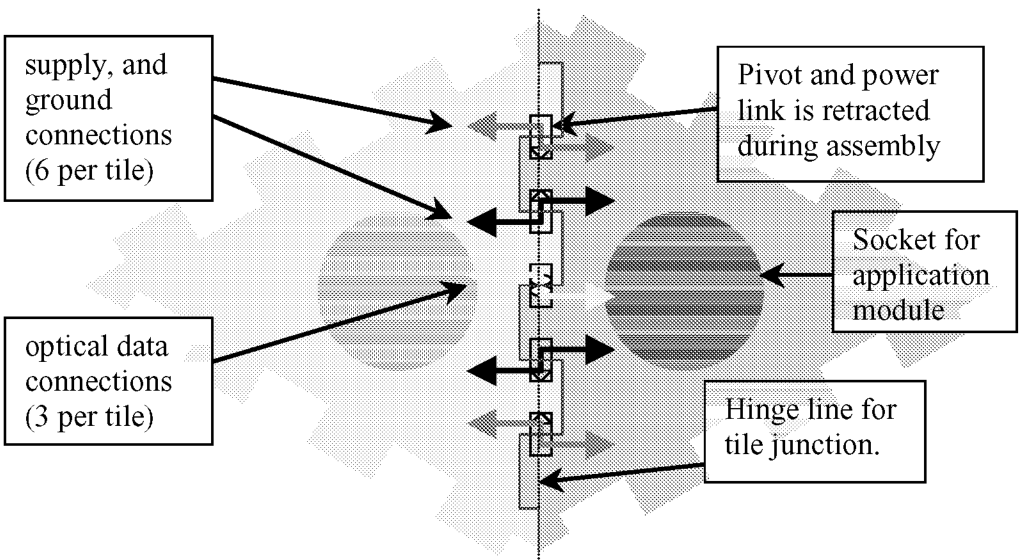
Design notes

- Aim to create “intelligent” self assembling structures.
- Can self-assemble “plates”, “beams”, computational and sensory arrays.
- Provide redundant power and data links.
- Can self-diagnose and replace failed elements.
- For space applications – ideally where arrays of sensors etc. are used.
- Not for re-entry or high-speed atmospheric use.

The basic tile unit

The triangular tiles are rotationally symmetric. Each edge is capable of connecting to any other tile edge. This specification has the side effect of defining a "top" face and a "bottom" face for each tile – tiles can only link with their "top" faces in the same direction. A variation to this scheme requires a second type of tile that provides the link between the tiles (see later notes).

Each edge of each triangular tile has two power and two ground connections, to couple power into and out of the tile. In addition it has an optical data communications link between pairs of adjacent tiles.



- Each tile contains significant computational and communications ability. It must be able to self-diagnose, run consistency checks on its neighbours, read its sensors, control its actuators, work out where its "master" is, negotiate new links after reconfiguration, and even take on new roles if required by external command, or by loss of external control. It is likely that a standard cell would contain some basic sensing equipment for, say, strain, temperature, damage etc., as well as the ability to control the power coupling links, and the transport mechanism.

- The power connections act as the pivots for a hinge mechanism that permits tiles to change the angle between their faces from about 70 to 290 degrees[7]. The power links are axial on the hinge line, and retract to allow assembly and disassembly of the tiles. Tiles must cooperate to link and unlink. If a tile failure results in the inability to unlink the defective tile, the tile's neighbours will be sacrificed and replaced. The

[7] 70.5 degrees is the approximate included angle for a regular tetrahedron – and the included angle for the fan folding structures shown below. This range enables an "upward" or "downward" fan fold.

power links are multiply redundant (6 per tile) and are capable of sinking and sourcing power. The electronics for power control is built into the tile.

- The optical data communications links are also hinge-axial so that data flow is not dependent on the angle between the communicating tiles. Each link is able to support not only data for the tile itself, but to carry high volumes of data from adjacent tiles, or even trunked data from remote tiles. A tile can continue to communicate with the array if only one of the three links is active. The data flow and transceiver electronics are built into the tile.

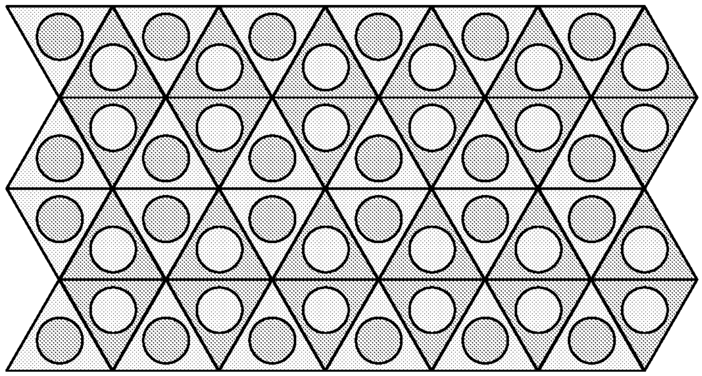
- Each tile has a socket that can carry an application module. The module could be any one of several types:
    - Solar power module – providing power to the grid.
    - Power storage module – for local/regional load balancing.
    - Specialist sensor elements – either individual or as part of an array.
    - Antenna elements – perhaps as part of a phased array.
    - Display elements – a self-assembling display module is possible.
    - Computational hardware – the default computing hardware may not be adequate for some tasks.
    - Regional supervisory system – perhaps extra memory and intelligence to run a large part of the system. A standard node must be able to be a local supervisor to allow for redundancy, but it may not be reasonable to allow every tile the resources to run a major section.

  A typical high-level system would involve many applications, e.g. a remote sensing platform with solar power and wireless remote data retrieval.

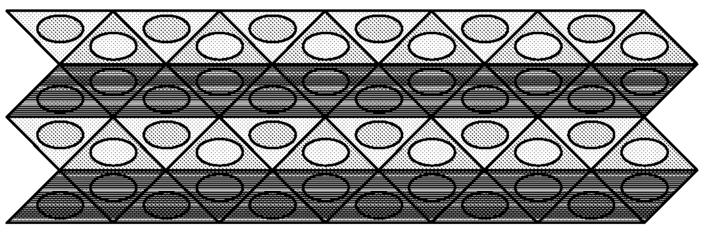
- Each tile has two or three (mechanical, power and data) link points to allow for an articulated arm to move across its face. The arm may be either permanently associated with each tile or may be dynamically assigned to "walk" across the array of tiles. It is this articulated arm that permits the assembly of the tiles. It is strong enough to carry new (or defective) tiles across the surface, and to pull the tiles into the correct physical orientation for their application. It gains its power and data links from the tile to which it is connected. The arm is controlled by a virtual agent process which moves through the tile array with the arm. As a temporary additional power and data link between two tiles, it can be used to permit analysis and control of a tile with dysfunctional data ports. During construction, new (or replacement) tiles would move down a "bucket brigade" of arms to their final destination. Articulated arms could have either two "hands" or three "hands". A two-handed arm could sit in a fixed position as a "cilium" to pass tiles overhead to the next arm, or it could remain attached to a moving tile, as one of a pair of arms that let the tile "walk" across the array. A three-handed arm could carry a tile while walking across the array. It is not inconceivable to supply every tile with a set of 2 or 3 permanent arms of its own, so it became effectively mobile in its own right. In this way a tile could be viewed as an autonomous micro-robot, being powered and communicating through the array structure as it walks. Obviously it would need to keep at least one "foot" on the ground.

Mechanical structures

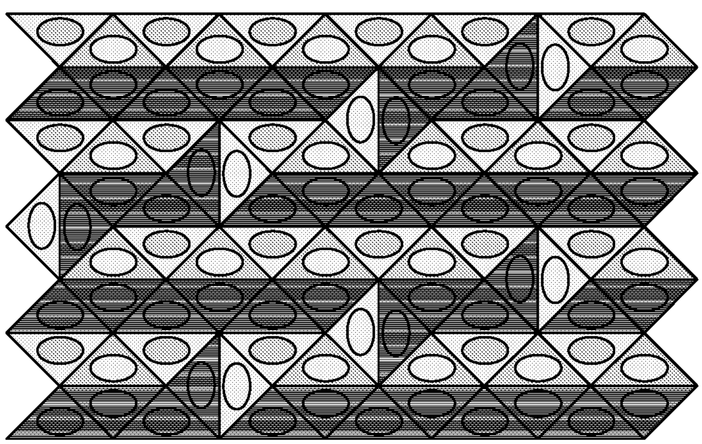
The hinged nature of the tiles results in significant flexibility, or even weakness, when in the form of a simple planar interlocked array, such as that shown below.



Structural weakness can be overcome by fan folding.

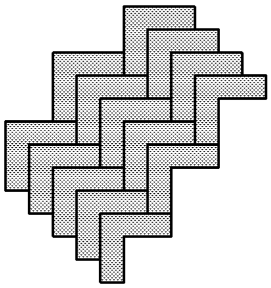


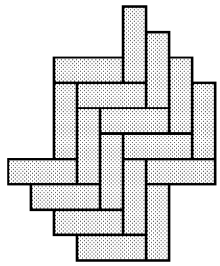
The stiffness of the structure can be enhanced by lateral interlocking.

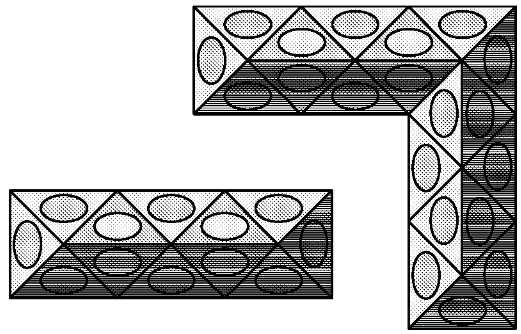


The triangular tiles can be arranged to form square (or even pentagonal) meta-structures, which permit the assembly of ribbed, but rectangular "plates" to make more traditional rectangular structures, as well as a wide range of geodesic look-alikes.

Rigid sheet structures of many forms are possible. One sub-category is rectangular blocks or “L” shapes as below. A quasi-plane can be generated from a tessellated array of rectangles in a herringbone pattern, or interlocked “L” patterns. The rigidity varies with block length.







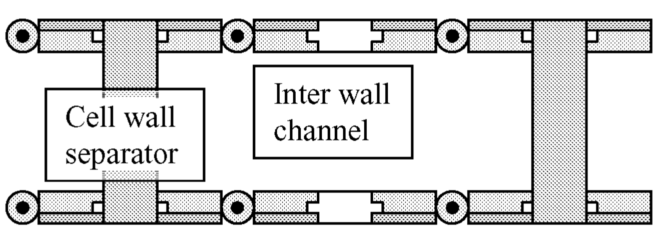
It should be clear that the hinge mechanism is neither fluid nor gas tight – so as presented above the tiles are not a complete solution. Some possible variations will be noted later.

Alternative tile edge connection

It is not hard to define a double-hinged edge structure, where tiles can be connected with three-way rotational symmetry as well as tolerating back-front reversal. It requires a roughly rectangular strip that has a “hinge” on each side which connects to the edge of a tile. Because tiles never connect to each other directly (only through a “hinge” block) the tiles can be symmetric across the three lateral dividing axes (instead of antisymmetric so they can interlock). Additional benefits include the increased range of angles, 0 to 360 degrees, and no dependence on another tile to detach. Liabilities include the increase in connection counts (double the number of mechanical links), and a reduction in rigidity since there are now two hinges that set the tile-to-tile angle. There would probably be a need for six optical links to adjacent tiles, to maintain axial coupling along the hinge line.

Bilayer tile structures

The cell array has an upper and a lower face. Thought of as an inner and outer face, a double layer may be considered with the inner faces connected, and outer faces exposed to the world – like a biological cell wall. It is not hard to contemplate a surface made of such a bi-layer where the transport mechanism occurs between the layers. Such channels would be rather like “veins” through which “nutrients” were delivered. The assumption is not of fluid flowing through the channels, but of articulated arms passing packets. The cell wall separator could be made of standard tiles. Such a structure is illustrated below.



A4.2 Responsive skeletons

It would be appealing to have the frame or skeleton of a vehicle able to automatically strengthen in response to stress (similar to the increase of bone density in response to exercise). This would let the system evolve to meet changing requirements. What was once a single-walled beam made of tiles or blocks, could be turned into a 3D array of interlocked beams, with new layers of structure added if the structure senses a stress approaching some limit.

Note that, just like a real skeleton, the increase in strength is not instantaneous. A sudden overload will damage the system if it is too weak.

One attractive feature of such a "techno-skeleton" is that, not only can it respond to stress, it can also be electronically "pre-evolved" to meet known or planned requirements.

A4.3 Artificial dynamic surfaces

A4.3.1 Grow and shed bark

The particular challenges of a shuttle-type vehicle, which must withstand repeated ablation damage in a self-healing fashion, has led to the idea of a bark-like skin which is grown on an artificial surface, and can peel to give a new undamaged surface. The idea comes from many of the eucalypt family of trees, which shed the dead outer layer of bark as the newer layer grows underneath[8].

One option is an integrated biological skin on the surface of the vehicle. There are some serious limits to this.

- Tree bark grows quite slowly – waiting a year for the next flight is a little slow.
- Tree bark is combustible – not a good surface for an ablation shield.
- The bark is relatively soft.
- The shedding of a fairly thick skin may be a problem, in terms of lost material.

There are tougher plant materials, such as bamboo, which have high silica contents in their outer structures, and are very strong for their weight, forming a natural scaffolding material. Bamboos have no equivalent to the bark peeling of the eucalypts.

A technological version of bark might be created, by secreting a series of different layers through the skin of a vehicle to create a skin with varying properties, for example. The external skin would consist of layers growing from the inner production surface. An ablation-protection skin might consist of layers of ceramic-loaded epoxy separated by layers that readily separated once exposed, to enable the outer layer to shed fairly quickly, once penetrated.

[8] Creating the interesting comment that, in contrast to European trees, eucalypts keep their leaves but shed their bark.

There are many other possible skin characteristics which could be generated by such a dynamic skin surface. It is not hard to imagine loading the skin layer with conductive, dielectric, or even absorptive materials, or even growing complex optical multi-layer interference filters. If such a surface were possible, it would be the technological equivalent of a chameleon, with an almost arbitrary radar cross-section.

If the skin is a flow/lift surface, there must be some mechanism to control surface texture, such as bark peeling (internal control), or surface abrading (external agent). See also subsection A4.3.4.

A4.3.2 Epoxy foam

Reference was made in the main report (subsection 4.5) to a material in which small cracks cause microcapsules of polymer to burst, which in turn react with a catalyst to seal the crack before it has time to spread far. An obvious limitation of this system is dealing with large cracks that require large volume filling very quickly. If there was a layer of pressurized epoxy foam, that oozes, expands and sets on exposure to some external initiator (vacuum, air, heat, etc.), penetration of the surface would result in the rapid expansion of the epoxy foam to fill the cavity. Such a system could rapidly fill and seal a medium-sized puncture, as a “first aid” response. It may be stored as a gel under the skin and activate when the damage occurs.

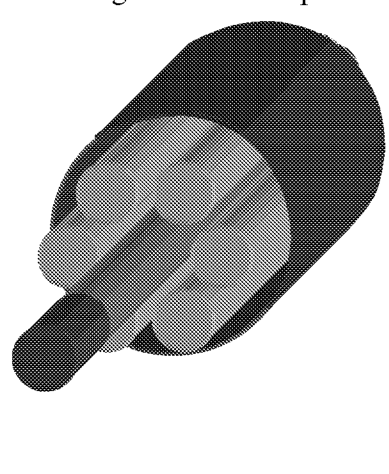
The idea of artificial “bark” and the idea of “foam” are attractive. A hybrid may be possible – a kind of epoxy foam which bleeds and “clots” on the surface, hardening to provide a seal and an ablation surface.

This is analogous to many trees, which deal with sudden damage by oozing sap to fill gaps. The sap hardens to protect the damaged surface. If a small area is damaged the hardened sap may eventually be shed – if a larger area is damaged the hardened sap may be grown over by new layers of wood. This may be similar in principle to, but less complex than, the healing of soft tissue in humans (see Section 3).

A4.3.3 Continuously growing sensors

The conflicting requirements of a growing skin layer and intimate surface sensing led to the idea of sensors that grow with the skin. This problem is faced by most (all?) biological systems. The solution is small sensor structures that penetrate the skin surface. Skin hairs are, among other functions, highly sensitive sensors that grow and are replaced while the skin around them also grows and is replaced.

A synthetic fibre may be grown at the same rate as the artificial “bark” layer, to maintain contact with the surface, or even to extend beyond the surface. Such a fibre could be of constant cross section and density, or could be optimized to have more mass nearer the tip, increasing the sensitivity to motion (a synthetic otolith).



The sensor could operate with a strain gauge at its root. An array of parallel fibres may use the stress in a central fibre to change the coupling of energy (either optically in transparent fibres, or electrically in a capacitive sensor) differentially to the surrounding fibres.

A4.3.4 Artificial scales/feathers

The possible requirement for a morphable surface which is capable of large area change as well as repeated movement with no degradation, led to the idea of a flexible, growing, aerodynamic surface. Bird feathers create a highly flexible aerodynamic surface, which does not depend heavily on any single feather. Similarly fish scales cover a highly flexible surface that is optimized for a fluid flow environment. The scales on reptiles similarly allow great flexibility.

A tensegrity frame may be used to define a wing/fin surface, with a finely structured tensegrity surface creating a finer mesh structure, with the same high levels of morphability. If a feather- or scale-growing element were placed at each node of the finer structure, an artificial segmented outer covering would create the aerodynamic surface that may generate lift.

If in addition to growing the feather or scale the control unit could actuate it, then it would be possible to modify local turbulence around the wing to optimize lift and drag. There have been other suggestions for methods of controlling surface texture, as mentioned in the main report (Section 4.4), for example by using MEMS structures (see http://ho.seas.ucla.edu); however, this technique is specifically designed to deal with ongoing damage to the surface, with the actuator buried under the exposed surface.

If the feather or scale-growing element could grow material fast enough, a silica-loaded scale might even grow sufficiently to regenerate between re-entry ablation episodes.

A4.3.5 Vectored micro-thrust

NASA is already considering the use of Synthetic Jets as replacements for traditional aileron, elevator, and rudder structures. If the wing interior were slightly pressurized, an array of micro-vents could control local turbulence/lift/drag characteristics on the surface of the wings.

The wings of newer commercial jet liners carry winglets at their tips to improve aerodynamic performance. Could a synthetic winglet be created using a controlled air jet?

A4.4 Tile regeneration

Regardless of differences in details of individual tile design, the surfaces discussed above will require maintenance and/or regeneration. While various aspects of these issues have been discussed throughout the report, an idea for a simple structure is outlined here.

Such a structure might consist of the following:

- a spherical outer surface (e.g. the Figure A4.4.1 below, or even simpler),
- a multi-layer skin,
- a multi-chamber skeleton,
- single units (triangular tiles) as building blocks, and
- hierarchical, delocalized information processing.

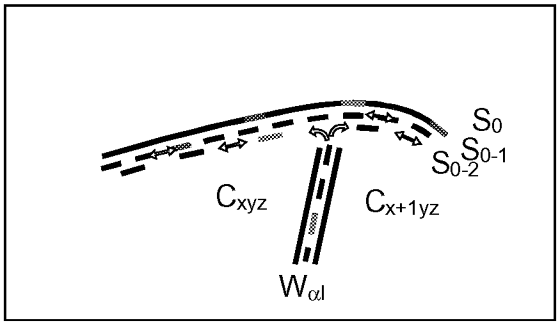


Figure A4.4.1: The floating tiles model

A detailed description of the model

1. S_0 is the outer compact shell. S_{0-1} is the first inner shell and so on. Due to the lower tile density in the inner shells, tiles may move quicker in these (inner) shells to replace defective tiles in S_0. This process proceeds in principle without any decision making process; it is defined as a tile characteristic in combination with their condition within the shell. The tiles are floating (diffusion), flip-flopping, or distributed by robots. The constraints on tile's mobility will centre around their energy consumption and the time it takes for various actions to occur. A replacement may be random or directed, depending on the tile type (see below).

2. The interior is structured into sections and chambers C_{xyz}. Their walls, also formed by tiles, are hollow and transport the tiles to the outer shell, regulated by demand (or density gradient).

3. All tiles connected to their neighbours transfer information. This produces, *inter alia*, a "bit" of information, which denotes whether a tile is to be replaced or not. Step-by-step more sensors (stress, temperature, etc.) can be integrated into the tiles. The available information increases commensurately; for example, temperature can be measured as one bit ("normal" or "not normal") or multi-bit information; the time regime is flexible. The model has to deal with a wide range of possibilities.

4. Tiles have different responsibilities. The hierarchical structure is given by (see Figure A4.4.1):
   - black tiles - sensor and connector,
   - blue tiles - sensor and connector, low-level centre for information processing,

- red tiles - sensor and connector, high-level centre for information processing, etc.
- algorithms to control information distribution and processing, decision making (for example: further tile replacement or replacing a section), cognitive characteristics, etc.

A4.5 Computational aspects

A4.5.1 Distributed role differentiation by numerical gradients.

There are analogues to biological systems in which the chemical gradients that allow differentiation in cells can be mimicked. For example:

- An edge tile (identified by having a side with no neighbour) can transmit its location and existence to a higher processing level by sending out its ID with a token that is incremented as it passes through each adjacent tile, thus making a numerical gradient denoting the communication path, and hence the tile's position. This needs a way of pruning to the "lowest" token number to avoid loops.
- The presence of a master node can be identified by the reverse mechanism – a "master" is identified by a master code, its ID and a distance token being regularly transmitted through the system.
- If the master node is lost (i.e. the transmitted "distance" code is invalid) a new master can be "elected" by some kind of weighted statistical competition (with random backoff) if conflict occurs.

There are many other differentiation options that can be organized in this way.

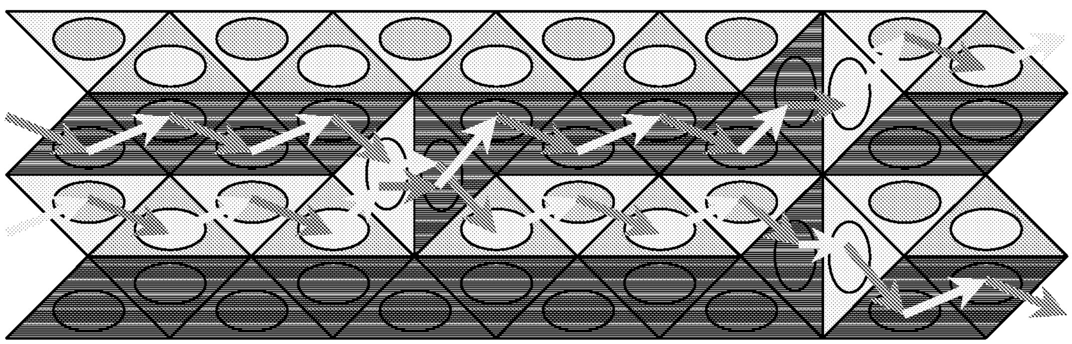
A4.5.2 Computational and connectivity issues

Address navigation for sending and replying to messages
If each tile appends a 1 or 0 depending on the direction (left or right) in which a forwarded message is passed on from its source, the appended bit sequence can be followed back to the sender. Note that, for a large tile array, the address sequence could get rather long, but its length is proportional to the square root of the number of tiles, not to the number of tiles. In practice addressing might be done in a hierarchical mode, so the actual address length might be reduced to addresses within a hierarchy.

Another problem, which appears somewhat complex, is that some communications are going to be broadcast into the array (see below). Given that much data is going to be repeated by adjacent tiles, how are endless, cascading, loops of repeated messages halted? The simplest way is to assign an identity to a tile, but for a very large number of tiles a unique identity may be expensive to send around. It seems likely that most potential loops will occur in a local region, so all that needs to be transmitted is a hashed version of the source identity, and a hashed version of the message identity, which probably only need to be unique within the local region. (Hashing is a method of applying an algorithm to a string of bytes without regard to the significance of the string, thereby generating addresses that are likely to be relatively evenly distributed and, being deducible from the parent string, make for rapid look-up of records, in this case the source and message identities.)

Mechanically assembled systolic computational arrays
The large array of computational tiles is very similar to a systolic processor array. One of the limits of such systems is the difficulty of reconfiguration of the array to match real problems. A typical systolic array is well matched to only a limited set of problems. Does an automatically reconfigurable systolic array provide benefits?

One interesting logical/geometrical relationship is that a signal can be sent in a "straight" line through the system by a repeated series of L, R, L, R, … , L, R "turns" as it enters and leaves the tiles. An unusual effect occurs if one of the "cross-bracing" structures is used. In this case the change in physical structure produces a physical crossover of signals. Time has not permitted the investigation of the idea for a mechanically reconfigurable cross-point switch, or other data exchange structures, like FFT butterflies.



<u>*A4.5.3 Virtual entities*</u>

Autonomous virtual objects
Autonomous micro-robots (AMRs) are an appropriate solution to some problems, but create some concerns about the power and communications aspects of self-contained autonomous agents. An AMR needs at least the three following abilities to function:

- Autonomy – to implement a plan or procedure.
- Mobility – to move around the vehicle.
- Actuation – the ability to physically modify their environment.

It seems that the first two abilities don't need independent hardware. A virtual object could be created, either located in a particular node of a system, or even distributed over several nodes, and linked to other objects by the communications network. Such an "autonomous virtual object" (AVO) could move by taking itself off the task list of one cell and transferring it to an adjacent one. One very attractive side effect is the ability to clone itself. The major loss of functionality in trading AMRs for AVOs is the removal of a redundant hardware system, in that AVOs are wholly dependent on the network for their existence.

Agent plus arm as an autonomous micro-robot
Apart from the loss of an independent computational source, an AVO linked to an articulated arm is not far from an AMR. Software agents, which move from tile to tile controlling a simple articulated arm and move with the arm, represent a kind of micro-robot with its intelligence or "self" located outside of its "body"[9].

Distributed virtual entities
A side effect of these thoughts is the idea of a "Distributed Virtual Entity" (DVE). While each cell in an array of cells might have local sensors, many quantities that need to be sensed require sensor results from many nearby cells[10]. It is possible to define a software entity that is distributed across many cells as a compound sensor. As with the AVO such a DVE is mobile, and can clone itself or self-destruct with no hardware costs at all. The central planning systems might tell every major communications node to create a dozen DVEs to go off and search randomly (or concertedly) for local hot spots, unusual stress patterns, or even to "go out and get" a thermal map of the left wing tip and "bring" it back as an image.

[9] A sort of technological "out of body" experience.
[10] This issue was discussed in Section 8.5 of the report, where the proposed solution, the use of "supertiles", is similar to that proposed here.

A5. Appendix to Section 5: Sensors

This Appendix contains material generated and discussed by the Sensors Working Group, including detailed information used as a basis for some of the discussion in the main body of the report. It is set out as follows.

A5.1 Micrometeoroids and orbital debris.
A5.2 Particle radiation in space.
A5.3 Worksheet: vehicle types and their functional sub-systems.
A5.4 Worksheet: threats and consequences.
A5.5 Worksheet: threats and measurands.
A5.6 Worksheet: high priority sensor types.

A5.1 Micrometeoroids and orbital debris

Orbital debris is any man-made object in orbit about the Earth that no longer serves a useful purpose. It constitutes all derelict spacecraft, the upper stages of launch vehicles, their effluents, flecks of paint, debris from explosions, etc. At present about 10,000 objects larger than 10 cm are known to exist, more than 100,000 objects between 1 cm and 10 cm, and 100 million or more objects smaller than 1 mm. The average impact velocity of particles with other space objects is about 10 km s^{-1}. Micrometeoroids are solid particles that occur naturally in our solar system. These are small but numerous: the interplanetary flux of particles of mass one gram is about 10^{-15} m^{-2} s^{-1}, rising to about 10^{-2} m^{-2} s^{-1} for particles of mass 10^{-16} g. The spatial density of debris is known, peaking around an altitude of 1000 km (at over 10^{-8} objects km^{-3}), declining to about 10^{-12} objects km^{-3} at about 40,000 km then decreasing quickly at higher altitudes. There are peaks in the density near 20,000 km and 36,000 km, and in the polar and equatorial planes.

The convention for referring to orbital debris by size is as follows. Large debris has a diameter greater than 10 cm, a mass greater than 1 kg, and therefore may be able to be catalogued in low Earth orbit (LEO, less than 2000 km) and would, on collision, probably cause the loss of a spacecraft. Medium debris, with diameters between 1 mm and 10 cm, mass between 1 mg and 1 kg, are generally too small to catalogue and too few in number for *in situ* sampling, but whose effects on spacecraft range from surface degradation through component damage to possible loss of spacecraft capability. Small debris, less than 1 mm in size, and less than 1 mg in mass, is detectable only by *in situ* sampling, and can cause surface degradation and possible damage to unprotected components.

Both radar and optical telescopes are used to track large debris from the Earth, with the detectability limit of these techniques, roughly, being about 2 cm diameter objects up to about 500 km, 5 cm up to a few thousand km and about 1 m at geostationary orbits around 35,000 km. Several experiments, such as the Long Duration Exposure Facility (LDEF), the Orbital Meteoroid and Debris Counter, and several detectors on interplanetary exploration spacecraft, have been implemented to characterize both the size and constitution of orbital debris and micrometeoroids, as well as the effects of the space environment on a wide range of materials.

The mean time between impacts on spacecraft of cross-sectional area 10 m^2 for each size category of debris has been calculated, and peak (at altitudes of 1000 km) at 3-30 years for objects 0.1-1.0 cm, 700-1,400 years for objects 1-10 cm and 20,000 years for objects larger than 10 cm. NASA uses an acceptable risk criterion of 1 in 100,000 as a chance of collision.

Mitigation of the effects of collisions with debris range from detection (from Earth) and avoidance for the large debris (physical protection against particles larger than 10 cm is not yet technically feasible), to the shielding of spacecraft for medium and small debris. In the medium range, shielding is effective against particles between 1 mm and 1 cm, but in the range 1 cm to 10 cm protection takes the form of design of spacecraft structures (redundant subsystems, frangible structures, pressure vessel isolation, maximum physical separation of redundant components and paths of fluid and electrical lines, etc.), as well as careful selection of spacecraft attitude. Shielding designs vary from Whipple bumpers, to complex layers of metal and ceramic/polymer fabrics designed to break up the impacting particle, with the energy of the resulting ejecta being absorbed.

References

The information in this summary has been obtained from a number of sources available on the Web. Some of the more general sources are listed below.

http://mtrs.msfc.nasa.gov/mtrs/97/rp1408.pdf
NASA reference publication 1408: "Meteoroids and Orbital Debris: Effects on Spacecraft", C. A. Belk et al., August 1997. An excellent summary.

http://mtrs.msfc.nasa.gov/mtrs/94/rp1350.pdf
NASA reference publication 1350: "The Natural Space Environment: Effects on Spacecraft", B. F. James et al., November 1994. Discusses the neutral thermosphere, thermal environment, plasmas, meteoroids and orbital debris, solar environment, ionizing radiation, magnetic fields, gravitational fields, mesosphere.

http://www.orbitaldebris.jsc.nasa.gov/
Johnson Space Center – orbital debris capital of the world

Orbital Debris Quarterly News
http://www.orbitaldebris.jsc.nasa.gov/newsletter/news_index.html

Orbital Debris: A Technical Assessment (1995)
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United Nations *Technical Report on Space Debris* (1999)
http://orbitaldebris.jsc.nasa.gov/miscell/UN_Report_on_Space_Debris99.pdf

A5.2 Particle radiation in space

A brief summary of the threats posed by particle radiation in space is given below. It does not consider electromagnetic radiation, which is also potentially hazardous to man and materials. High-energy em radiation (from UV to X-rays) is emitted by the sun, both continually and in higher-intensity bursts. Appropriate shielding is required for any biological material. Degradation of external materials will also occur, and this should be mitigated by appropriate material selection, and material degradation monitored.

Glossary of terms

GCR	Galactic Cosmic Rays
HZE	Ions of high charge and energy
LET	Linear Energy Transfer
SEP	Solar Energetic Particles

Particle radiation in space

Radiations in space are from three primary sources and consist of every known particle, including energetic ions formed from stripping the electrons from all of the natural elements. The radiations are described by flux probabilities for each particle type over a selected spatial domain as a function of time. The three sources of particle radiation are identified as:

i. Particles of galactic origin (Galactic Cosmic Rays, GCR).
ii. Particles of solar origin, produced by the acceleration and ejection of solar plasma (Solar Energetic Particles, SEP).
iii. Particles trapped within the confines of a planetary geomagnetic field.

The radiation exposure of a spacecraft depends upon the mission location and duration and has a significant dependence upon chance as to whether a high-energy solar flare occurs during the mission. Furthermore the interior radiation (within a spacecraft), experienced by astronauts and equipment, differs significantly from the external radiation due to the fragmentation of incident high charge and energy (HZE) ions and the production of secondary light ions and neutrons.

High-energy particle radiation is defined as electrons with energies greater than 40 KeV, protons or neutrons with energies greater than 1 MeV, and heavy ions with energies above 1 MeV/nucleon. Lower energy electrons, protons, and ions are ubiquitous and are defined as plasma.

Galactic cosmic rays

The GCR constitute a low-intensity background radiation constant outside the solar system, but modulated in a region within several AU of the Sun by changes in the interplanetary plasma over the solar cycle (the lower energy galactic ions are excluded). The fluxes experienced at 1 AU from the Sun are about an order of magnitude lower during a solar maximum compared to those during a solar minimum. High-energy GCR events can occur if the astronomical event generating the radiation is nearby.

Accumulated GCR is the major component of radiation exposure on long duration space missions. For crewed deep space missions the protection of astronauts against background GCR provides sufficient protection against the effects of SEP radiation, described below. GCR particles are in varying states of ionization and require mass shielding, as magnetic shielding cannot deflect uncharged particles.

The best HZE shields are materials with high hydrogen content. These materials have a high number of electrons per unit mass, low excitation energy, and the shield particles have a low probability of being knocked free to become secondary radiation. Liquid hydrogen would be the best shield, but is regarded as impractical because of need to maintain cryogenic temperatures. Materials containing large amounts of hydrogen are second best, e.g. water (about half as good a shield as hydrogen), polystyrene, lithium hydride and magnesium hydride. Other materials such as beryllium, aluminium and lead are used in the fabrication of shields, but are designed into multi-layer shields, usually in combination with high hydrogen-content materials. Used alone they can produce large quantities of secondary radiation which may be more harmful to humans. Particle storm shelters within spacecraft may be necessary for humans during periods of high particle flux.

Solar energetic particles

SEPs are associated with some solar flares that produce intense bursts of high-energy plasma propagating into the solar system. SEP events are the greatest environmental uncertainty for deep space missions, and the main radiation concern for short duration space missions. Intense SEP fluxes can occur unexpectedly, delivering to humans a potentially lethal dose in a few hours which could cause death or serious radiation illness over the following few days to weeks. SEP events occur randomly within the solar cycle with intensities and spectral content differing greatly from event to event. Statistical models have been developed for the low energy (10 and 30 MeV) event fluence levels near Earth, but statistical models in the range of 50 to 100 MeV are unavailable.

As SEP particles are highly ionized, either mass shielding or magnetic radiation shielding (generated by superconducting magnets) provide protection.

Trapped radiation

The trapped radiations are local to Earth and other planets with geomagnetic fields. Terrestrial trapped radiations consist mainly of protons and electrons within two bands centred on the geomagnetic equator reaching a maximum at 3,600 km followed by a minimum at 7,000 km and a second very broad maximum at 10,000 km extending to 60,000 km. Known as the van Allen Belts, the inner belt is populated by high-energy (10's of MeV) protons and medium-energy (50-1000 keV) electrons, while the outer belt comprises predominately high-energy electrons.

Trapped radiations are experienced, for example, by a spacecraft in the passage from low Earth orbit (LEO) to interplanetary space. The radiation dose can be of some importance if the passage time is more than several minutes.

The *AP8/AE8* models are currently the principle source of data on the terrestrial trapped radiation environment. They are based on data from many different satellites. The P and E in the model names refer to Proton and Electron and 8 is the version number of the models. AP8 and AE8 provide estimates of the omni-directional fluxes of protons in the energy range of 50 keV to 500 MeV and electrons in the energy range of 50 keV to 7 MeV. Time-dependent variations of the radiation fluxes such as those due to geomagnetic storms or short-term solar modulations are not included in AP8/AE8. However, the models do differentiate between solar cycle maximum and minimum conditions.

Human exposure to radiation

A large component of the radiation exposure to astronauts is contributed by the ions of high charge and energy (HZE). Secondary electrons are produced by the interaction of the passing ion with the atomic electrons in the material. The electrons recoil from the ion impact at up to twice the speed of the passing ion and propagate the energy (in the human body) tens of microns from the ion path. The same radiation dose as produced by a single Fe ion would require several hundred protons, and, unlike the Fe ion, these would generally be randomly distributed. Thus, an HZE ion produces a relatively high, concentrated dose as compared with lighter ions. A second risk for the astronaut is the potential exposure to a random SEP event. The radiation safety factor required on crewed space missions significantly increases the mission cost. It is estimated that for a Mars mission improving models of GCR would reduce mission cost by as much as $40B. Improving the models of the way in which shielding materials respond to HZE ions would allow a further $30B cost reduction. There has been much work on the effects of exposure to space radiation, particles and electromagnetic waves.

Electronic exposure to radiation

Some recent research at NASA has looked at post-mortem identification of the causes of satellite failure. Electronics failure is often caused by a single HZE ion impacting semiconductors. Damage is caused either through ionization and electrostatic discharge, or the displacement of atoms by the impact. Gate failure in FET devices is commonly due to a single HZE ion impacting near the FET gate.

Detection of high-energy particles

Low-energy particles are usually detected by measuring the ionization of the matter through which they pass. These detectors include cloud chambers, ionization chambers, spark chambers, Geiger-Müller counters, proportional counters, scintillation counters, solid-state detectors, photographic emulsions, and chemical etching of certain mineral crystals or plastics in which ionization damage is revealed. Detectors are designed to measure the rate at which a particle slows, thereby gaining information about their energy and type. Cerenkov detectors and transition radiation detectors are used to study higher energy particles. Very high energy particles are studied by observing the large showers of secondaries they produce in Earth's atmosphere, detected either by counting the particles which survive to strike ground-level detectors or by looking at the flashes of light the showers produce in the atmosphere.

In general terms ionizing particle radiation may be detected using a gamma/x-ray detector with a suitable shield material in front of the detector to generate gamma radiation from the incident radiation. Many detectors may be used in parallel behind different shields to detect different energy particles. For electrons, protons and HZE particles aluminium is a common shield material, while cadmium or samarium are used for neutrons. There are many types of gamma and X-ray detectors:

- CdZnTe. Bulk Cadmium Zinc Telluride 3x3x3mm. Single photon detection for energies of 70 keV - 180 keV with 5 keV resolution.
- Semiconductor doped optical fibre, atoms put into higher energy level by ionizing radiation until pumped by heat (IR) when they thermoluminesce.
- Silicon PIN diode.
- CsI PIN diode.
- pFET self-biased as a current regulator. Ionization within the FET channel is detected as a change in FET bias current.
- Miniaturized ionization chamber.

SEP events are simultaneous with X-ray bursts, and so severe X-ray bursts may be used as an indication (warning) of a major SEP event, arriving at the Earth (1 AU) about 20 minutes before the particles.

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Vehicle Type:		***AU: space vehicle - uncrewed (contains no bio-material)***	***AC: space vehicle - crewed***	***B: vehicle in permanent earth orbit - crewed***	***C: shuttle - crewed***	***D: aircraft - crewed***
Outer Skin						
	Shielding (radiation, particles)	Thermal, em(UV, X-rays), cosmic, solar particle radiation, micro-meteoroids.	Thermal, em (UV, X-rays), cosmic, solar particle radiation, micro-meteoroids.	Thermal, em (UV, X-rays), cosmic, solar particle radiation, orbital debris, micro-meteoroids	Thermal, em (UV, X-rays), cosmic, solar particle radiation, orbital debris.	Thermal, em (UV).
	Aerodynamic surface	No	No	No	Yes	Yes
	Pressure vessel	Yes (may be within vehicle)	Yes	Yes	Yes	Yes
	Windows	No	Yes	Yes	Yes	Yes
Structural skeleton		Yes	Yes	Yes	Yes	Yes
	Frame					
	Engine mountings					
	Landing, docking gear					
Propulsion system						
	Engine	Rocket, ion beam, solar, nuclear, …	Rocket, ion beam, solar, nuclear, …	Rocket	Rocket	Jet (Fan/turbine), rocket
	Fuel delivery system					
	Fuel storage	Liquid, solid	Liquid, solid	Liquid, solid	Liquid, solid	Liquid, solid
Energy (non-propulsion)						
	Generator	Nuclear, thermoelectric	Nuclear, thermoelectric, fuel cell		Nuclear, turbine	Turbine
	Battery system	Yes	Yes	Yes	Yes	Yes
	Solar panels	Yes	Yes	Yes	Deployable	No
	Energy distribution					
Electronic systems		Yes	Yes	Yes	Yes	Yes
	Control systems (including gyroscopes)					
	Navigation system					
	Communications system					
	Sensing, monitoring systems					
Life support/comfort systems		No	Yes	Yes	Yes	Yes
	Atmosphere: composition, pressure, temperature					
	Water					
	Food					
	Waste disposal/recycling					
	Light, sound					
	Entertainment					

A5.3 Vehicle types and their functional sub-systems

Vehicle AU: Uncrewed Space Vehicle.

Subsystem	*Threat/consequence*	*Worst-case Consequence*	*Serious-ness (1-5)*	*Time to Respond*	*Immediate Response*	*Primary Measurand(s)*	*Secondary Measurand(s)*
Shielding (outermost skin)							
	Impact: meteoroids, space junk	Substantial hole in shield	4	Minutes	Repair	Radar for detection of threat	Elastic impact detection, network continuity, optical assessment of damage
	Impact: dust, micrometeoroids	Surface damage, small hole	2	Hours	Repair	Elastic impact detection	Optical assessment of damage, network continuity
	Material failure: radiation damage (thermal, em, cosmic)	Widespread damage	5	Hours/days	Repair	Detect threat: radiation	Optical, ultrasonic inspection (active)
	Material failure: fracture, cracking, debonding	Severe damage	4	Minutes	Repair	Detect precursor: material degradation	Optical, ultrasonic inspection (active), network continuity.
	Material degradation: fatigue, erosion (eg by charge effects), corrosion (eg due to atomic oxygen).	Precursor to material failure	2	Days	Repair	Detect causes: stress, charging, chemical atmosphere, etc.	Detect fatigue, microcracking, material loss, corrosion, etc.
Pressure vessel (inside radiation shield)							
	Impact: meteoroids, space junk (large, medium/large)	Substantial hole in PV, rapid loss of pressure	5	Immediate	Avoidance, or rapid isolation of damaged section (similar to redundancy)	Radar for threat detection, elastic impact detection & location	Network continuity, optical assessment of damage
	Impact: dust, micrometeoroids (small, medium/small)	Surface damage, small hole	4	Seconds	Temporary repair	Autonomic detection and (temporary) repair, elastic impact detection.	Optical assessment of damage, network continuity, active ultrasonic inspection.
	Material failure: fracture, cracking, debonding	Severe damage to PV, loss of pressure	5	Immediate	Avoidance by detection of precursor, redundancy by over-engineering.	Detect precursor: material degradation. Failure detection by acoustic emission	Optical, ultrasonic inspection (active). Network continuity check.
	Material degradation: fatigue	Precursor to material failure	2	Hours/days	Repair	Fatigue, microcracking detection	
	Leaks (seals etc.)	Loss of pressure	4	Seconds	Temporary repair	Acoustic emission.	Pressure loss, gas flow.
	Explosion	Severe damage to PV, loss of pressure	5	Immediate	Avoidance by detection of preconditions, or rapid isolation of damaged section.	Detect presence of explosive components - leaks, contamination, heat, spark.	Elastic shock wave detection. Network continuity.
	Fire	Severe damage to PV, loss of pressure	4	Seconds	Avoidance by detection of preconditions, or extinguish fire early and repair	Detect presence of combustible components - as for explosion	Detect heat, smoke.
Structural frame							
	Impact: meteoroids, space junk (large, medium/large)	Substantial damage to structure	5	Immediate	Avoidance, or sacrifice of damaged structure.	Radar for threat detection, elastic impact detection & location	Network continuity, optical assessment of damage
	Material failure: fracture, cracking, debonding, …	Substantial damage to structure	5	Immediate	Avoidance by detection of precursor, redundancy by over-engineering	Detect precursor: material degradation. Failure detection by acoustic emission	Optical, ultrasonic inspection (active). Network continuity.
	Material degradation: fatigue, creep, corrosion, …	Precursor to material failure	2	Hours/days	Repair	Detect fatigue, creep, corrosion, …	
	Explosion	Substantial damage to structure	5	Immediate	Avoidance by detection of preconditions.	Detect presence of explosive components - leaks, contamination, heat, spark.	Elastic shock wave detection. Network continuity.
	Fire	Substantial damage to structure	4	Seconds	Avoidance by detection of preconditions, or extinguish fire early and repair	Detect presence of combustible components - as for explosion	Detect heat, smoke.
Engine mountings							
	As for structural frame						
Docking gear							
	As for structural frame						

A5.4 Threats and consequences

Engine (rockets + ion/solar/nuclear/ ...)							
	Fuel leak	Loss of fuel, precursor to explosion	4	Immediate	Avoidance by detection of precursor, or temporary repair	Detect material degradation, cracking prior to leak.	Fuel pressure loss, acoustic emission
	Fuel blockage	Loss of engine function	3	Seconds	Shut down engine and clear	Fuel flow rate, pressure	
	Fuel contamination	Loss of engine function	3	Minutes	Shut down engine and clean	Chemical sensors ("taste" sensor)	Flow, optical properties of fuel
	Explosion	Substantial damage to engine, vehicle	5	Immediate	Avoidance by detection of precursor (leak, radiation, ...).	Detect leak, detect contaminant(s). Monitor nuclear parameters (if applicable).	Elastic shock wave detection. Network continuity.
	Impact: meteoroids, space junk (large, medium/large)	Substantial damage to engine	5	Immediate	Avoidance, isolate engine & fuel system	Radar for threat detection, elastic impact detection & location	Optical assessment of damage, network continuity.
	Impact: dust, micrometeoroids (small, medium/small)	Less significant damage to engine	2	Depends on engine (minutes-hours)	Shut down, inspect, repair	Elastic impact detection	Optical assessment of damage, network continuity.
	Material failure: radiation damage (thermal, cosmic)	Widespread engine damage	4	Minutes	Repair	Detect radiation, heat	Optical, ultrasonic inspection (active) when engine off
	Material failure: fracture, cracking, debonding	Substantial damage to engine	5	Immediate	Avoidance by detection of precursor	Detect precursor: fatigue, erosion, ... Failure detection by acoustic emission.	Optical, ultrasonic inspection (active) when engine off. Network continuity.
	Material degradation: fatigue, erosion, embrittlement ...	Precursor to material failure	2	Minutes/hours	Repair	Detect fatigue, erosion, embrittlement, ...	
	Control system failure	Loss of engine control	3	Seconds	Shut down engine and repair	Self-diagnostics, engine performance monitoring	
Fuel delivery system (pumps, pipes, seals, etc.)							
	Leaks	Loss of fuel, contamination, precursor to explosion	4	Immediate	Avoidance by detection of precursor, or temporary repair	Detect degradation, microcracking, cracking in lines	Detect fuel in external areas ("smell"). Fuel flow, pressure
	Blockages	Loss of engine function	3	Seconds	Shut down engines and clear	Fuel flow, pressure	Engine performance monitoring
	Pump failure	Loss of engine function	3	Seconds	Shut down engine and repair/redundancy	Material degradation. Fuel flow, pressure	Acoustic monitoring
	Explosion	Substantial damage to vehicle	5	Immediate	Avoidance by detection of precursor (leak).	Detect fuel leak, source of ignition	Elastic shock wave detection, network continuity.
	Impact: meteoroids, space junk (large, medium)	Substantial damage, fuel leakage.	5	Immediate	Avoidance, isolate fuel system.	Radar for threat detection, elastic impact detection & location	Optical assessment of damage, network continuity.
	Material failure: fracture, cracking, debonding	Fuel leakage	5	Immediate	Avoidance by detection of precursor.	Detect precursor: fatigue, wear, ... Failure detection by acoustic emission.	Optical, ultrasonic inspection (active). Network continuity.
	Material degradation: fatigue, wear, dry seals, ...	Precursor to material failure	2	Minutes	Repair	Detect fatigue, wear, seal condition, ...	
Fuel storage							
	Fuel leak	Loss of fuel, contamination, precursor to explosion	4	Immediate	Avoidance by detection of precursor, or temporary repair	Detect degradation, microcracking, cracking, debonding in tank.	Chemical sensing ("smell") outside tank
	Fuel contamination	Loss of engine function	3	Minutes	Shut down engine, clean fuel	Chemical ("taste") sensing in storage tank	Optical absorption spectroscopy
	Explosion	Substantial damage to vehicle, fuel loss.	5	Immediate	Avoidance by detection of precursor (leak).	Detect fuel leak	Elastic shock wave detection, network continuity.
	Fire	Fuel loss, damage, explosion	4	Immediate	Avoidance by detection of precursor (leak).	Detect fuel leak	Detect heat, smoke
	Impact: meteoroids, space junk	Substantial damage, fuel loss.	5	Immediate	Avoidance, isolate fuel tanks	Radar for threat detection, elastic impact detection & location	Optical assessment of damage, network continuity.
	Material failure: fracture, cracking, debonding	Substantial damage, fuel loss.	5	Immediate	Avoidance by detection of precursor.	Detect precursor: fatigue, ... Failure detection by acoustic emission.	Optical, ultrasonic inspection (active). Network continuity.
	Material degradation: fatigue	Precursor to material failure	2	Minutes	Repair	Detect fatigue	
	Environmental control system failure	Fuel degradation, precursor to explosion	3	Minutes	Redundancy	System self-diagnostics	Environment monitoring (T, P, ...)
Generator							
	Reactor failure (fuel, control, material failure, ...)	Loss of power, radiation leak	5	Minutes	Redundancy	Material degradation, temperature, radiation levels, ...	
	Explosion	Damage to vehicle, radiation leak	5	Immediate	Avoidance by detection of precursors	Monitor nuclear parameters	
	Turbine failure (wear, lubrication, material failure, ...)	Loss of power	5	Minutes	Redundancy	Detect material degradation, lubricant flow and condition, ...	Power output
	Thermoelectric source failure (material, joint failure, ...)	Loss of power	5	Minutes	Repair, redundancy	Detect loss of electrical output.	

A5.4 Threats and consequences (cont.)

Solar panels							
	Impact: meteoroids, space junk (large, medium/large)	Damage (widespread) to panels	3	Minutes/hours	Redundancy	Radar for threat detection, elastic impact detection & location	Network continuity, optical assessment of damage
	Impact: dust, micrometeoroids (small, medium/small)	Minor damage to panels	2	Hours/days	Redundancy	Elastic impact detection	Network continuity, optical assessment of damage
	Electrical failure	Power loss	5	Minutes	Repair	Electrical performance monitoring	
	Material failure: radiation damage (thermal, cosmic)	Widespread damage (minor?)	3	Hours/days	Repair	Detect threat: radiation	Optical, ultrasonic assessment (active).
	Material failure: fracture, cracking, debonding	Substantial damage to panels	4	Minutes/hours	Redundancy	Detect precursor: fatigue, ... Failure detection by acoustic emission.	Optical, ultrasonic inspection (active). Network continuity.
	Material degradation: fatigue	Precursor to material failure	2	Days	Repair	Detect fatigue	
Energy distribution							
	Material degradation and failure (conductors)	Power loss	5	Hours	Detect early and repair	Material degradation, electrical properties	
	Material degradation and failure (insulation)	Precursor to fire, explosion	5	Hours	Detect early and repair	To be determined.	
Control systems (electronic)							
	Computer failure (temp., radiation, elec	Loss of control	5	Immediate	Redundancy	Self-checking diagnostics	Temperature, electrical properties, ...
	Software error	Loss of control, incorrect control	5	Immediate	Avoidance by self-checking	Self-checking diagnostics	
	Loss of information	Loss of control, incorrect control	5	Immediate	Avoidance by self-checking	Self-checking diagnostics	
	Communication failure (cables, wireless, etc.)	Partial loss of control	5	Immediate	Redundancy	Self-checking diagnostics, electrical continuity	
	Actuator failure	Partial loss of control	5	Immediate	Avoidance by detction of precursor	Monitor material degradation, electrical, mechanical responses.	
Navigation system							
	Optical, em antennae failure	Loss of information	5	Hours	Redundancy, repair	Monitor response, system self-check	
	Computer failure (temp., radiation, elec	Loss of navigation ability	5	Minutes/hours	Redundancy, repair	Self-checking diagnostics	Temperature, electrical properties, ...
	Software error	Incorrect navigation	5	Minutes/hours	Avoidance by self-checking	Self-checking diagnostics	
	Loss of information	Incorrect navigation	5	Minutes/hours	Avoidance by self-checking	Self-checking diagnostics	
	Communication failure (cables, wireles	Loss of information/navigation ability	5	Minutes/hours	Redundancy, repair	Self-checking diagnostics, electrical continuity	
Communications system							
	Antenna failure: impact, radiation, mate	Loss of communications	3	Hours	Redundancy, repair	Monitor response, system self-check	
	Transmitter/receiver failure (temperature, radiation, electrical, material, ...)	Loss of communications	3	Hours	Redundancy, repair	Monitor response, system self-check	
	Computer failure (temp., radiation, elec	Loss of communications	3	Hours	Redundancy, repair	Self-checking diagnostics	Temperature, electrical properties, ...
	Software error	Reduced or incorrect communications	2	Hours	Avoidance by self-checking	Self-checking diagnostics	
	Loss of information	Reduced or incorrect communications	2	Hours	Avoidance by self-checking	Self-checking diagnostics	
Sensing, monitoring system							
	Sensor failure	Vehicle vulnerable to damage	3	Minutes	Repair	Self-checking diagnostics	Vehicle damge
	Communications failure	Vehicle vulnerable to damage	3	Minutes	Repair or redundancy	Self-checking diagnostics	Vehicle damge
	Intelligent system failure	Vehicle vulnerable to damage	3	Seconds	Redundancy	Self-checking diagnostics	Vehicle damge

A5.4 Threats and consequences (cont.)

Vehicle AU: Uncrewed space vehicle

Most Serious Threats	***Subsystem most seriously affected***	***Measurand 1***	***Measurand 2***	***Measurand 3***
Impact: large, medium/large objects (meteoroids, space junk)	All	Radar etc. for early detection	Elastic impact detection and location	Optical assessment of damage. Check sensor network continuity.
Material failure: fracture, cracking, debonding, …	Pressure vessel	Detect material degradation: fatigue, corrosion, microcracking, debonding, …	Failure detection by acoustic emission	Optical assessment of damage. Check sensor network continuity.
	Structural frame (inc. engine mountings, docking gear)	"	"	"
	Engine	"	"	"
	Fuel delivery system	"	"	"
	Fuel storage	"	"	"
	Energy distribution system	"	"	"
	Generator	"	"	"
	Radiation shield	"	"	"
	Solar panels	"	"	"
Material failure: radiation damage (thermal, cosmic), charge effects	Radiation shield	Detect radiation levels	Acoustic emission monitoring	Active NDE (ultrasonics, optics, etc.) for damage evaluation.
	Engine	Temperature	Vibration (for some engine types)	Thrust (accelerometer)
	Electronic systems	Temperature, radiation, charge	Self-checking diagnostics	
Electronic failure	Control systems	Power loss, temperature	Self-checking diagnostics	Particle radiation, charge build-up
	Navigation	Self-checking diagnostics	Particle radiation, charge build-up	
	Communications system	Self-checking diagnostics	Particle radiation, charge build-up	
	Sensing, monitoring system	Self-checking diagnostics	Particle radiation, charge build-up	
Electrical failure	Energy distribution system	Detect material degradation: fatigue, microcracking, debonding, wear, …	Electrical power, current loss, temperature.	
	Generator, solar panels	"	"	Detect material degradation: radiation damage (to solar panels)
Fuel leaks	Engine	Detect material degradation: fatigue, microcracking, debonding, wear, …	Acoustic emission	Chemical sensing, pressure loss
	Fuel delivery system	"	"	"
	Fuel storage	"	"	"

A5.5 Threats and measurands

Explosion (fuel-related)	All	Detect fuel leak (above)	Detect presence of explosive components (chemical sensing - smell). Detect ignition source (electrical fault).	Elastic wave (shock) detection. Network continuity for damage assessment.
Explosion (nuclear)	Generator, propulsion system (if applicable)	Monitor nuclear conditions, radiation levels, temperature, etc.	Elastic wave (shock) detection.	Network continuity for damage assessment.
Explosion (other causes, e.g. major impact, excess pressure)	All	Detect precursor: see impact detection/avoidance, pressures.	Elastic wave (shock) detection.	Network continuity for damage assessment.
Fire	All	Detect flammable contaminants (chemical sensing), leaks (above), temperature, ignition source for prevention.	Smoke, heat detection	
Impact: dust, micrometeoroids (medium/small)	Radiation shield, Pressure vessel	Autonomic detection & temporary repair	Elastic impact detection	Damage assessment by optical, ultrasonic inspection (active).
Impact: dust, micrometeoroids (small)	Radiation shield, solar panels	Detect surface degradation		

A5.5 Threats and measurands (cont.)

Vehicle AU: Uncrewed space vehicle

Sensor type	***Measurand***	***Vehicle component***
Impact sensors (may be acoustic emission sensors)	Direct detection of impacts	Pressure vessel
		Radiation shield
		Structural frame
		Solar panels
Acoustic emission sensors	Material failure: fracture, cracking, debonding, …	All components
	Material degradation: fatigue, microcracking, etc.	All components
	Material failure: radiation damage	Radiation shield
	Fuel, pressure leaks, flow	Pressure vessel
		Fluid, pressure lines
		Fuel lines, fuel storage
	Explosions	
Optical (or em) damage assessment	Impacts	All components (mainly outer skin, pressure vessel)
	Material failure (all types)	All components.
	Explosions (all types)	All components
Sensing network continuity	Impacts	All components (mainly outer skin, pressure vessel)
	Material failure (all types)	All components.
	Explosions (all types)	All components.
Radiation (external): em (UV, X-rays), particle (cosmic, solar), thermal	Radiation levels	Radiation shield
	Particle radiation	Electronic systems
Radiation (internal)	Radiation levels	Reactor, power generator (if nuclear)
Charge accumulation	Charge, potential difference	Radiation shield
Temperature sensors	Temperature	Fires - all components
		Engine operation
		Electronic systems monitoring
		Energy distribution system
		Reactor, power generator
		Other (multi-modal) sensors
Pressure sensors	Liquid, gas pressures	Pressure vessel
		Fuel storage
		Fuel lines - leaks, blockages.
Chemical sensors - selective	Smoke (particles), contaminants in gases, liquids	Fires - all components
		Flammable gas contaminants - all enclosed areas
		Fuel leaks
		Fuel contaminants
		Corrosion products
	Explosive mixture sensor	All components
Active NDE sensors (ultrasonic, optical, …)	Material degradation (fatigue, wear, erosion, debonding, microcracking, …)	All components. May be mounted on autonomous agents, used in conjunction with embedded sensors.

A5.6 High priority sensor types

A10. Appendix to Section 10: Summary and Conclusions

It's scary how relevant Douglas Adams can be...
The following is a quotation from Douglas Adams, 'Mostly Harmless', Harmony 1992.

Click, hum.

The huge grey Grebulon reconnaissance ship moved silently through the black void. It was travelling at fabulous, breath-taking speed, yet appeared, against the glimmering background of a billion distant stars to be moving not at all. It was just one dark speck frozen against an infinite granularity of brilliant night.

On board the ship, everything was as it had been for millennia, deeply dark and Silent.

Click, hum.

At least, almost everything.

Click, click, hum.

Click, hum, click, hum, click, hum.

Click, click, click, click, click, hum.

Hmmm.

A low level supervising program woke up a slightly higher level supervising program deep in the ship's semi-somnolent cyberbrain and reported to it that whenever it went click all it got was a hum.

The higher level supervising program asked it what it was supposed to get, and the low level supervising program said that it couldn't remember exactly, but thought it was probably more of a sort of distant satisfied sigh, wasn't it? It didn't know what this hum was. Click, hum, click, hum. That was all it was getting.

The higher level supervising program considered this and didn't like it. It asked the low level supervising program what exactly it was supervising and the low level supervising program said it couldn't remember that either, just that it was something that was meant to go click, sigh every ten years or so, which usually happened without fail. It had tried to consult its error look-up table but couldn't find it, which was why it had alerted the higher level supervising program to the problem.

The higher level supervising program went to consult one of its own look-up tables to find out what the low level supervising program was meant to be supervising.

It couldn't find the look-up table.

Odd.

It looked again. All it got was an error message. It tried to look up the error message in its error message look-up table and couldn't find that either. It allowed a couple of nanoseconds to go by while it went through all this again. Then it woke up its sector function supervisor.

The sector function supervisor hit immediate problems. It called its supervising agent which hit problems too. Within a few millionths of a second virtual circuits that had lain dormant, some for years, some for centuries, were flaring into life throughout the ship. Something, somewhere, had gone terribly wrong, but none of the supervising programs could tell what it was. At every level, vital instructions were missing, and the instructions about what to do in the event of discovering that vital instructions were missing, were also missing.

Small modules of software – agents – surged through the logical pathways, grouping, consulting, re-grouping. They quickly established that the ship's memory, all the way back to its central mission module, was in tatters. No amount of interrogation could determine what it was that had happened. Even the central mission module itself seemed to be damaged.

This made the whole problem very simple to deal with. Replace the central mission module. There was another one, a backup, an exact duplicate of the original. It had to be physically replaced because, for safety reasons, there was no link whatsoever between the original and its backup. Once the central mission module was replaced it could itself supervise the reconstruction of the rest of the system in every detail, and all would be well.

Robots were instructed to bring the backup central mission module from the shielded strong room, where they guarded it, to the ship's logic chamber for installation.

This involved the lengthy exchange of emergency codes and protocols as the robots interrogated the agents as to the authenticity of the instructions. At last the robots were satisfied that all procedures were correct. They unpacked the backup central mission module from its storage housing, carried it out of the storage chamber, fell out of the ship and went spinning off into the void.

This provided the first major clue as to what it was that was wrong.

Further investigation quickly established what it was that had happened. A meteorite had knocked a large hole in the ship. The ship had not previously detected this because the meteorite had neatly knocked out that part of the ship's processing equipment which was supposed to detect if the ship had been hit by a meteorite.

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13. ABSTRACT *(Maximum 200 words)*
This report discusses issues involved in the development of an intelligent health monitoring system for a future ageless aerospace vehicle. In almost all areas, analogies with biological materials, structures, processes and behaviours have been employed to provide insight and inspiration, even in cases where biological solutions are recognized to be inadequate or inappropriate to the requirements of an ageless vehicle. It was concluded that: 1) However advanced materials and structures become, there will be a requirement for a health monitoring system. 2) System design must be holistic and integrated: sensing, data processing, communications, learning and decision-making must all be considered as part of a single intelligent system. 3) Temporary (and multi-stage) responses to damage will be important to combat rapidly occurring or rapidly escalating damage. 4) A number of important sensing and measurement issues require solution, including embedding or integration of a range of sensors into materials (sensory materials), development of passive sensors for continuous monitoring, long-term reliability and accuracy of embedded sensors, etc. 5) There is a strong preference for implementing the system intelligence as a distributed multi-agent system. 6) The communication system will need to be parsimonious, architecturally simple, dynamically reconfigurable and capable of learning. 7) Data processing will need to be carried out on multiple levels, depending on the sensed data and the information required, in order to minimize response times and communication traffic.

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